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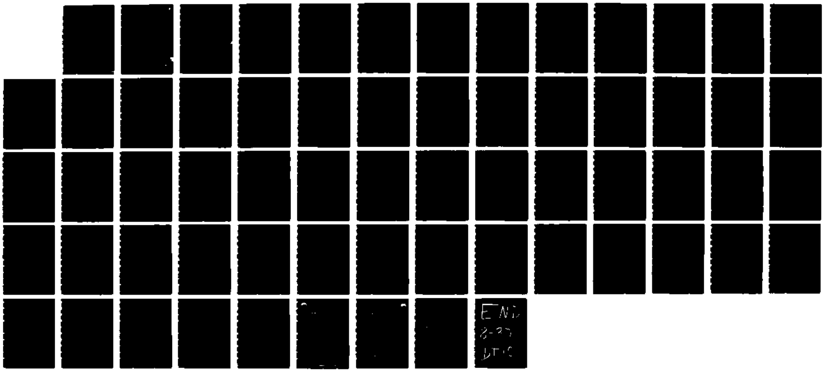

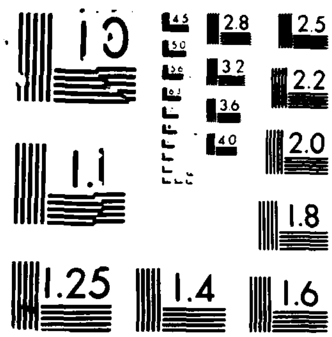
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This report covers the final stage of research by our group under AFOSR/DARPA sponsorship. During this contract period our research effort changed from the processing of long period data to the operation of the Lajitas short period station and the analysis of data from that station. The first section of this report covers the use of phase matched filters in the analysis of Rayleigh waves from events at the Semipalatinsk test site in the USSR. The second section reviews the analysis of ambient seismic background noise at the very quiet Lajitas station and a study of the magnitudes of signals recorded at Lajitas during our participation in the GSETT experiment during the last three months of 1985.

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FINAL TECHNICAL REPORT

to the

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Geophysical Laboratory
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Southern Methodist University
Dallas, Texas 75275

For The Period
15 October 1982 to 14 March 1985

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Title of Work:	Development of Seismic Signal Processing and Yield Estimation Techniques for Use at Regional to Teleseismic Distance

STUDIES AT THE LAJITAS SEISMIC STATION

Eugene T. Herrin

Introduction

The report describes ongoing studies based primarily on data obtained at the Lajitas site. The overall objective of these studies is to characterize seismic noise and signal in an extended frequency band, up to a bandwidth of 50 Hz or greater if possible. Knowledge of the broad-band, high frequency characteristics of regional signals and noise is essential in predicting the capability of a regional network of borehole and array stations to monitor small events as would be required in the verification of the terms of a low-threshold test-band treaty.

Lajitas Station

The Lajitas seismic stations is located in far West Texas just north of the Mexican border, about 10 miles west of the western entrance of Big Bend National Park. The site was selected for its remote location, being about 70 miles away from railroads, major highways or population centers. The remoteness of the site makes it possible to identify the source of most man-made seismic noise, and in many cases to eliminate that noise during periods in which high-resolution data is being recorded. The remaining seismic noise above some minimum background level comes primarily from the interaction of wind-induced turbulence with the ground surface in the vicinity of the station.

Figure 1 shows a plan of the vaults and boreholes in the central area of the Lajitas station. An additional 60 ft. borehole, not shown on the plan, is located about 50 meters to the west of the central pad.

LAJITAS SITE PLAN

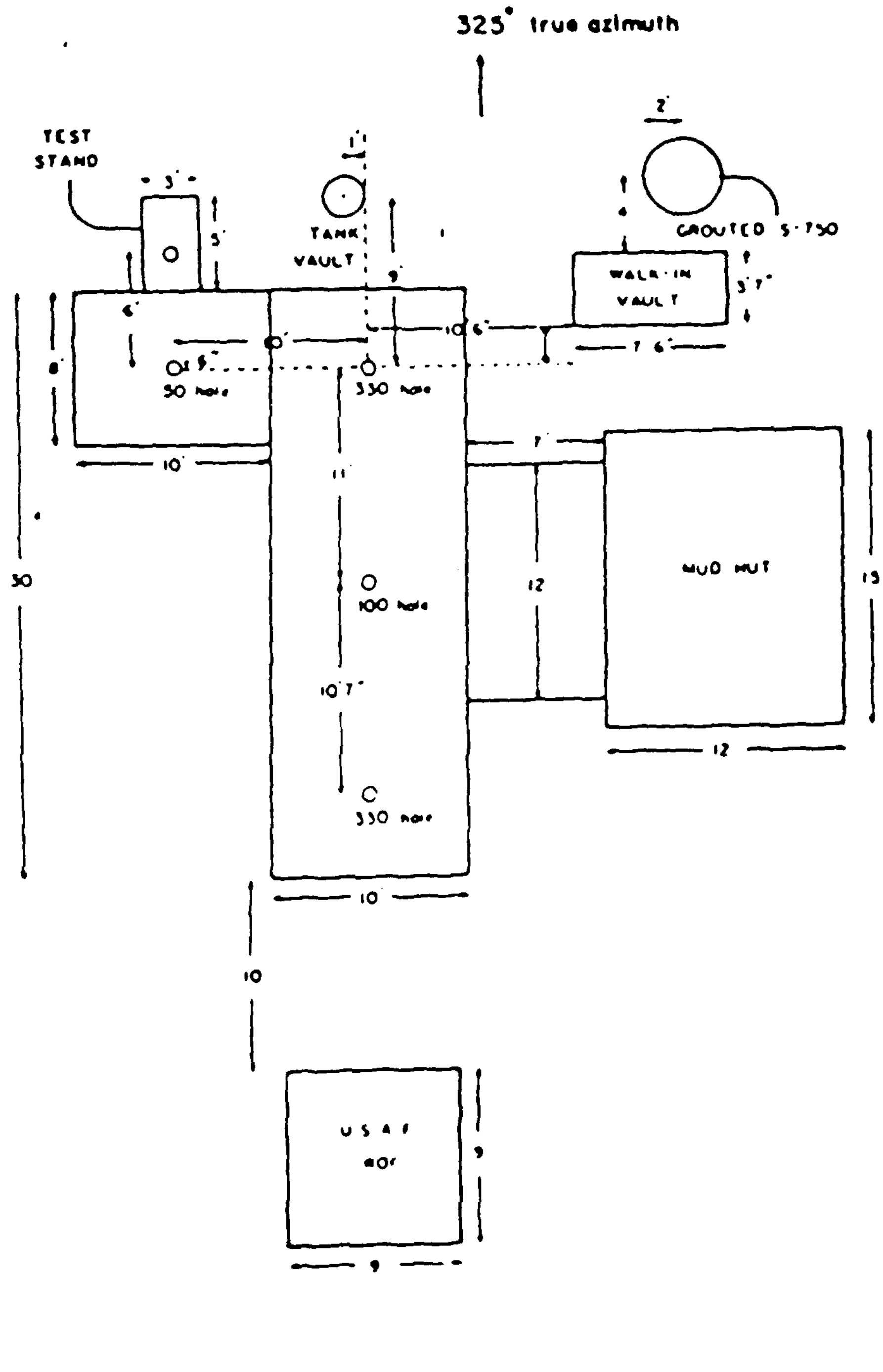

Figure 1

A number of tank vaults like the one shown in Figures 1 and 2 have been installed at distances from 50 meters to 500 meters away from the central area. Figure 2 is a schematic cross-section through the boreholes at the north end of the central area. All of the boreholes are cased with 7" API pipe except for the "Shallow borehole" (50 ft deep) shown in Figure 2 which has 9" API casing that can accommodate the new Teledyne-Geotech S-3 seismometer, identical to the model recently installed at AO in NORESS.

Instruments currently installed at Lajitas from which outputs are available are as follows:

S-750 -	Cemented into rock at a depth of 5 ft. (Z)
GS-13 -	Three components in vault (Z, N, E)
S-13 -	Two vertical units (Z) with battery powered amplifiers for use as portable units
GS-21 -	In 50 ft. borehold (Z component)
GS 21 -	In 330 ft. borehole (Z component)
KS-36,000 -	In 330 ft. borehole (AFTAC), Three component short period and long period outputs are available

S-21 (23,900) - In 100 ft. borehole (AFTAC), SP-Z.

In addition, FM analog data are available at Lajitas from S-21 (23,900) vertical sensors near Marathon, Texas, (MTX) about 75 miles north-northeast of Lajitas (LTX) and Shafter, Texas, (STX) about 60 miles northwest of Lajitas. The tripartite network formed by LTX, MTX and STX, and operated by AFTAC, is referred to as SOUS (Southern US) in the following discussions.

Two small buildings, two instrument trailers and a small living trailer are located at the Lajitas station. A third instrument trailer will be moved on site in the spring of 1986 to house a DEC LSI-11 which will become the second data recording system at Lajitas, sampling at 250 samples per second. A weight-drop machine and two super-woofers, with calibrated microphones, are available on site for use as controlled seismic sources. These sources have been used primarily for comparing instruments, studying instrument coupling and

LAJITAS SEISMIC STATION

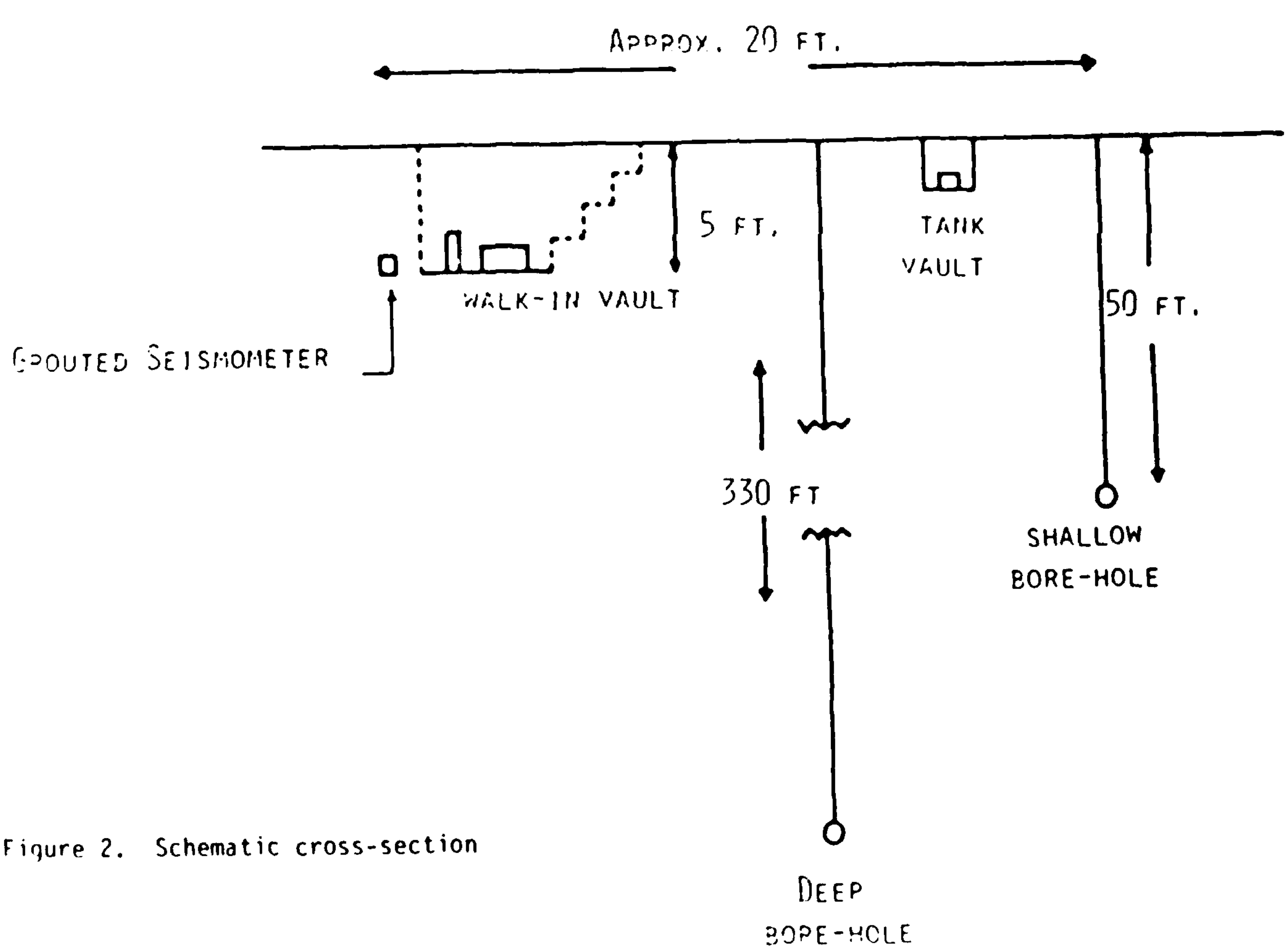

Figure 2. Schematic cross-section

simulating wind and aircraft noise. We intend to use these sources in the future to study borehole noise.

A data analysis system which we have found to be very useful in comparing sensors, identifying noise sources and obtaining broad-band noise spectra is composed of an HP-3582A spectral analyser, which uses the block-averaged estimation technique discussed later in this review, linked to an HP-85 personal computer. This system can be operated from a battery powered invertor and so can be truck mounted for observations away from the instrument trailers. The HP-85 software produced the plots shown in Figure 3. In this example spectra are shown to 50 Hz, but greater bandwidths are available because the system samples at a very high rate. In Figure 3, the outputs from two Z-component, GS-21 sensors at 50 ft. and 330 ft. depths are compared during a period when there was essentially no wind. We note that the coherence between these sensors is insignificant above about 10 Hz except for the spectral peak at about 26 Hz. This peak was observed for about three days, but vanished before we were able to identify the source.

We recently convened a workshop at Southern Methodist University where scientists from universities, government sponsored laboratories and industrial laboratories met to discuss the development of high-frequency seismic methods of interest in treaty verification research. The extension of seismic monitoring to bandwidths of 50 Hz means that the verification research community now has a great deal in common with the seismic exploration community in so far as the acquisition and analysis of seismic data are concerned. The explorationists suggested that, to be safe at least in the research mode, data analysis should not be attempted to frequencies much greater than about half of the Nyquist frequency. Their belief in this axiom is supported by the fact that seismic exploration data is now sampled at no less than 500 samples per second even though data processing bandwidths seldom exceed 100 Hz. We believe that systems designed to study seismic data to a bandwidth of 50 Hz should be sampled at 250 samples per second.

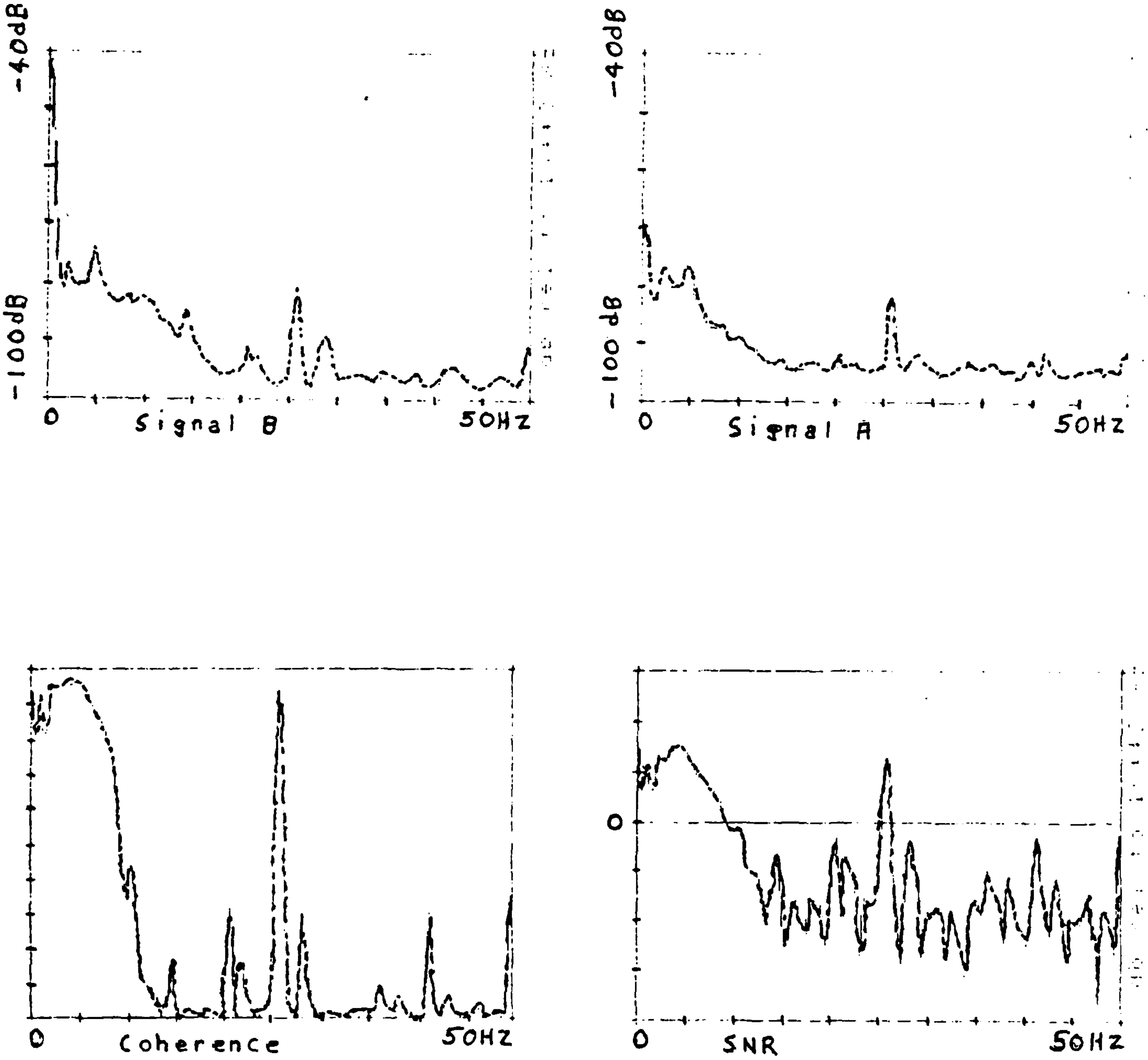

Figure 3. An example of the comparison of two-bore-hole seismometers made using the HP real-time analysis system. Signal B is from the 50 ft. Z sensor. Signal A is from the 330 ft. Z sensor.

The only two experimental systems supported by DARPA which will be sampling at this high a rate will be located at AO NORESS and at Lajitas. This spring, when an additional borehole system is installed at Lajitas, we will have an experiment directly comparable to the high-frequency experiment at NORESS, but in a very different geological and meterological environment. Data from these two systems will provide the base for examining seismic signals and noise at frequencies greater than the 10 to 15 HZ bandwidth provided by conventional RSTN and NORESS data.

<u>High-Frequency Noise Models</u>

Figure 4 shows the minimum reported noise levels (displacement power spectra) at Lajitas and NORSAR. It appears that the spectral noise level at Lajitas is about 10dB below the NORSAR (NORESS) level under quietest conditions. The levels will rise with increasing wind speed and with the occurrence of other disturbances such as vehicular traffic, aircraft, etc. at both sites. Figure 5 shows the rise in spectral noise level at Lajitas with increasing wind speed. We note that the two reported spectral measurements from NORSAR in high wind conditions show wind effects similar to those observed at Lajitas. Both the Lajitas data and the NORSAR data used in Figure 5 were from boreholes. We note from this figure that the wind-induced noise rises more rapidly with wind speed for higher frequency components. We believe that this effect will be present at all sites. The question then becomes one of the probability of occurrence of winds of a given speed.

In Figure 6 the zero to peak noise prior to signals reported for the Lajitas station during the two months of the GSETT experiment have been used to determine a cumulative probability of noise amplitude. Since the noise amplitude on the seismic record is dominated by the noise in the band 0.5 to 2.0 Hz, this probability distribution can be related to spectral noise in that band. The low-noise spectrum shown in Figure 4 will be observed less than 1% of time at Lajitas and so represents the left-hand toe of the curve in Figure 6. The broad upper part of this curve, which represents noise amplitudes

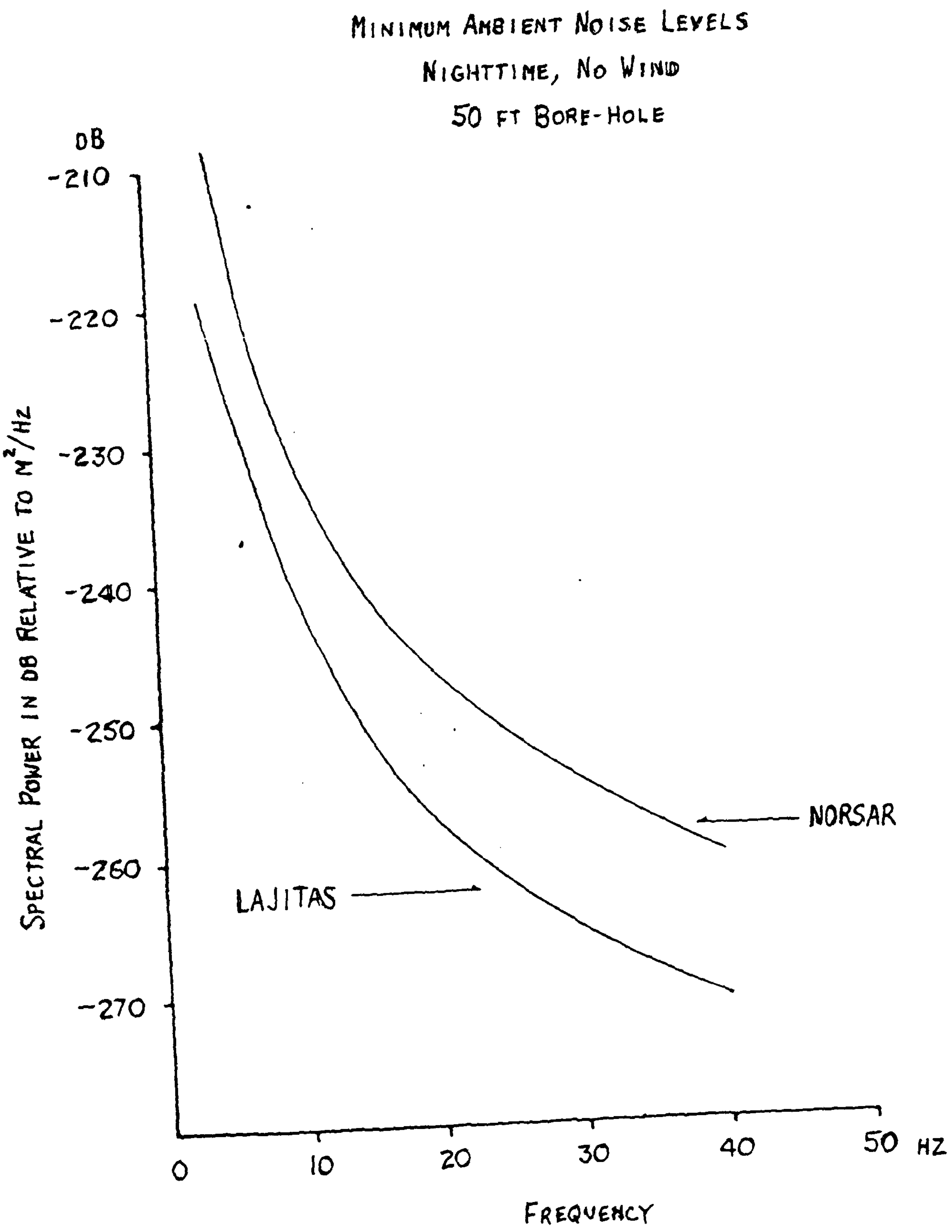
MINIMUM AMBIENT NOISE LEVELS
NIGHTTIME, NO WIND
50 FT BORE-HOLE
DB
-210
-220
-230
-240
-250
-260
-270
SPECTRAL POWER IN DB RELATIVE TO M²/HZ
NORSAR
LAJITAS
0
10
20
30
40
50 HZ
FREQUENCY

Figure 4.

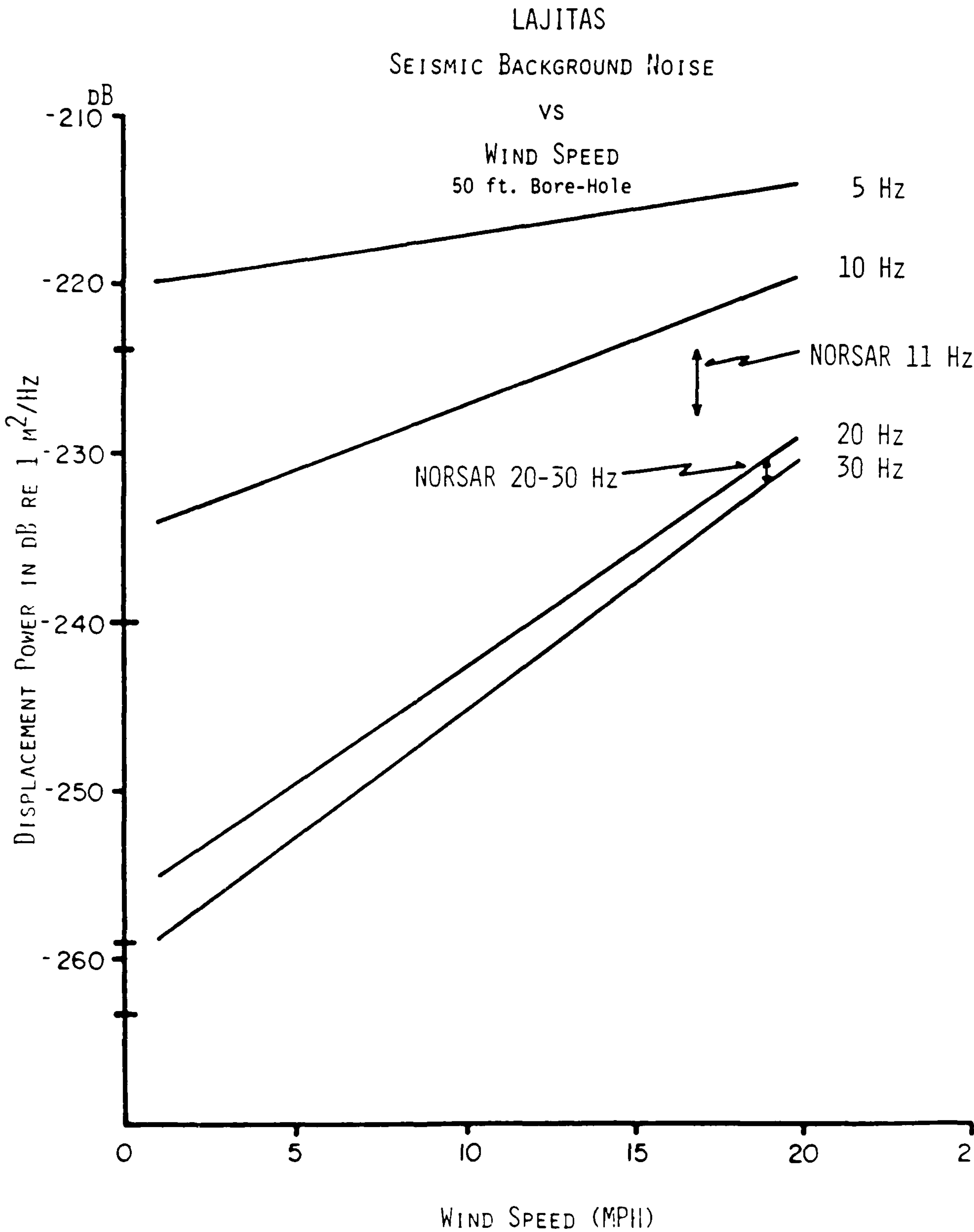
LAJITAS
SEISMIC BACKGROUND NOISE
VS
WIND SPEED
50 ft. Bore-Hole
dB
-210
-220
-230
-240
-250
-260
DISPLACEMENT POWER IN DB RE 1 M^2/HZ
5 Hz
10 Hz
NORSAR 11 Hz
20 Hz
30 Hz
NORSAR 20-30 Hz
0
5
10
15
20
25
WIND SPEED (MPH)

Figure 5.

Cumulative Probability
of Observed Noise Amplitude
(0.5 to 2.0 Hz)
Based on 1023 Observations
at Lajitas, Oct - Dec 1984

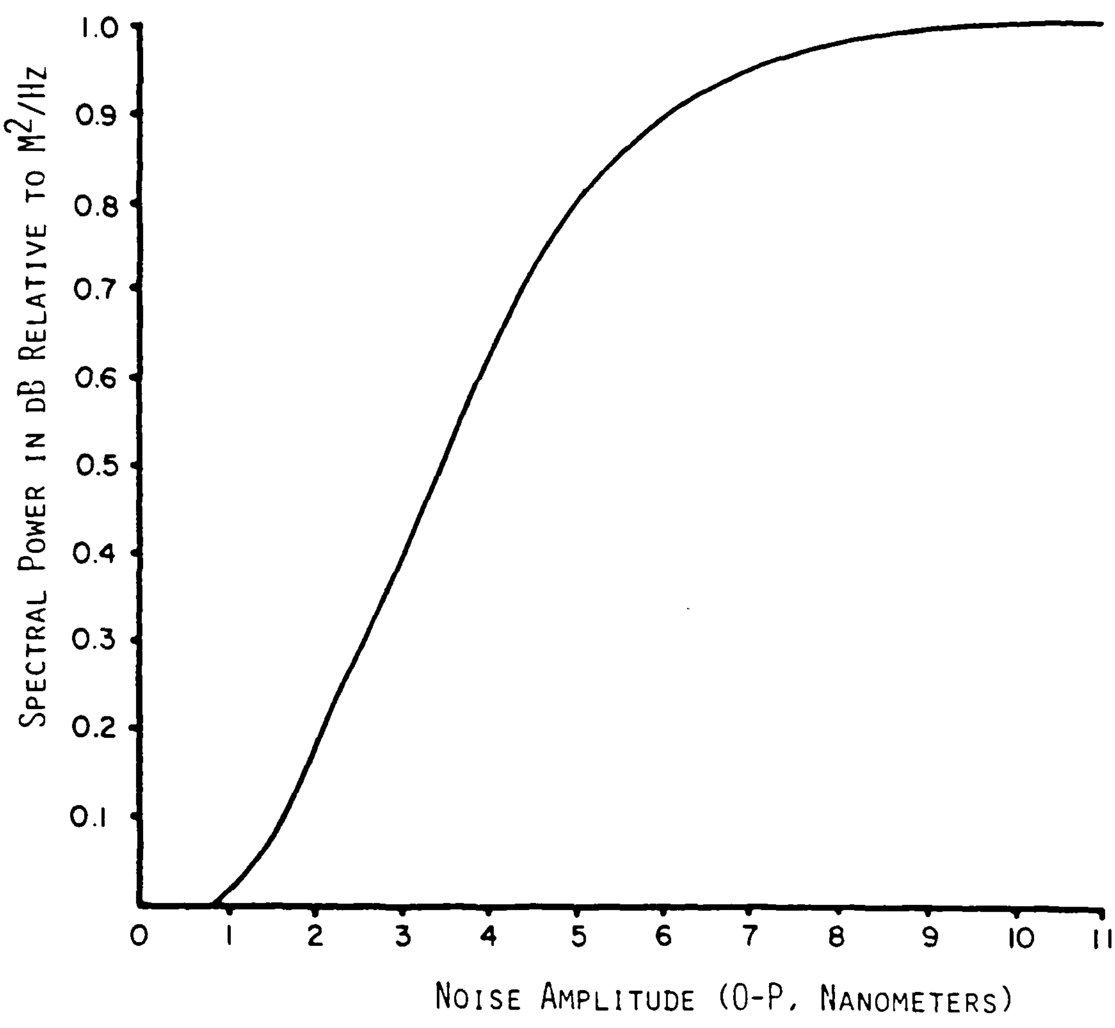

Figure 6.

greater than about 5 nanometers, represents periods of extremely high winds, human noise at the site, vehicular traffic, and the coda from events which extended into the noise window used for GSETT analysis. We do not know just how much of the noise probability distribution can be attributed to wind noise. Table 1 represents a first, and very tentative, attempt to predict what the percentile levels of spectral noise may be at Lajitas for frequencies higher than 2 Hz. These predictions should be confirmed or corrected using spectral measurements at the station, and a relationship between the cumulative wind speed probability and the cumulative spectral noise probability over the bandwidth of interest should be established for Lajitas.

No similar noise distribution for NORESS is available at this time, but we suspect that the data required to produce such a distribution are available from digital data at the C.S.S. What information we have indicates that the expected wind speed at NORESS is generally much lower than at Lajitas so that the median spectral noise levels in the 10 to 30 Hz band at the two sites may be about the same, although the lowest noise at Lajitas is about 10 dB below that at NORESS. In this case we would expect the 90-percentile wind noise level at Lajitas to be significantly greater than the NORESS level. In order to begin to characterize these noise probabilities for a variety of possible sites in the U.S.S.R., we must examine data from as many different sites as possible. Predictions based only on data from NORESS, where moderate to high wind speeds appear to be unlikely, could lead to capability estimates that would not be representative of most of the possible sites in the U.S.S.R. We intend to refine the noise probability estimates for Lajitas, develop similar estimates for NORESS, RSNT, RSON, RSSD and RSNY provided the required data are available, and to study the relationship between wind speed probability and noise probability. If relational models can be developed, then it may be possible to predict spectral noise probability at new sites based on available meteorological information.

In the long period seismic band boreholes have been very effective in reducing wind-induced seismic noise. Almost all of the long-period systems now used in treaty monitoring are located in boreholes. Wave-

PERCENTILE VALUES BASED ON
CUMULATIVE PROBABILITY OF NOISE LEVELS AT
LAJITAS - 50 FT. HOLE

PERCENTILE	AMPLITUDE (O-P, NANOMETERS) 0.5 - 2.0 Hz	INFERRED SPECTRAL LEVEL dB RE 1 M^2/Hz) 0.5 - 2.0 Hz	ESTIMATED SPECTRAL LEVEL (dB RE 1 M^2/Hz) 10 Hz	20 Hz
1%	1.0	-185	-240	-260
10%	1.5	-182	-236	-255
50%	3.5	-174	-228	-245
90%	6.0	-169	-223	-230
95%	7.0	-168	-222	-228

Table 1

length arguments could lead one to predict that borehole installations would be even more effective in reducing wind noise in the 0.5 to 50 Hz band, but this has not proved to be the case. Clearly other mechanisms for propagating these surface disturbances to depth take over at the higher frequencies. Higher mode surface waves, body waves and borehole waves have all been suggested as mechanisms, but the critical experiments have not been done. We intend to perform experiments at Lajitas using natural and artificial noise sources, and instruments at depths from 5 ft. to 330 ft. in order to better understand the propagation of high frequency surface noise into the borehole.

Teleseisms at Lajitas

Figure 7 shows a comparison of Lajitas Mb estimates to network maximum likelihood Mb estimates for teleseisms detected and reported during the two months of the GSETT experiment. This Figure shows that the Lajitas magnitudes are, on the average, slightly higher than the network values. Because teleseismic detection is almost always optimum in the 0.5 to 2.0 Hz band, the noise probability data from Figure 6 and the magnitude relations shown in Figure 7 can be used to model the teleseismic detection capability of Lajitas-like stations using codes such as NETWORTH and SNAP-D.

We have begun to estimate the detection capability for regional events at Lajitas. Preliminary analysis of regional events during periods when the noise level was low to moderate has shown that, in terms of Pn and Lg magnitudes, the single sensor detection capability at Lajitas is better than about magnitude 1.0 to 1.5 for P and 0.5 to 1.0 for Lg at distances of the order of 300 km, and is about magnitude 2.0 to 2.5 for P and 1.5 to 2.0 for Lg at distances of the order of 600 km. The relationship between this detection capability and noise probability or wind conditions has not yet been established.

Figure 8 shows a portion of a Helicorder record (Z component borehole sensor) from Lajitas for 27 NOV 1985. A number of local, regional and teleseismic events can be seen in this figure. An analyst picked 44 separate events on the entire record for this day. Perhaps a fourth of these are regional events which can be analysed for frequency content,

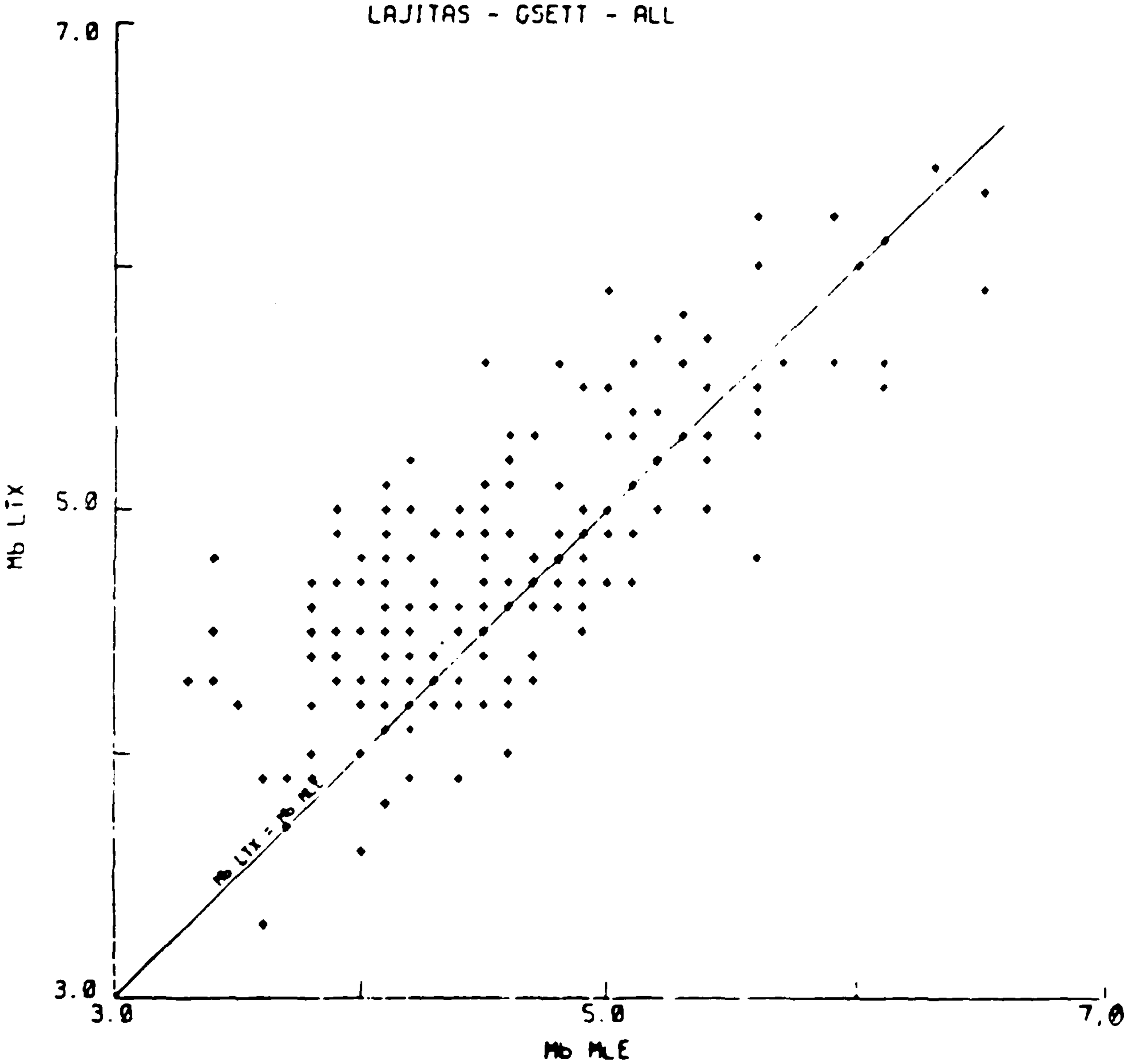

Figure 7. A comparison of Lajitas magnitudes and maximum likelihood network magnitudes for events reported during the GSETT experiment.

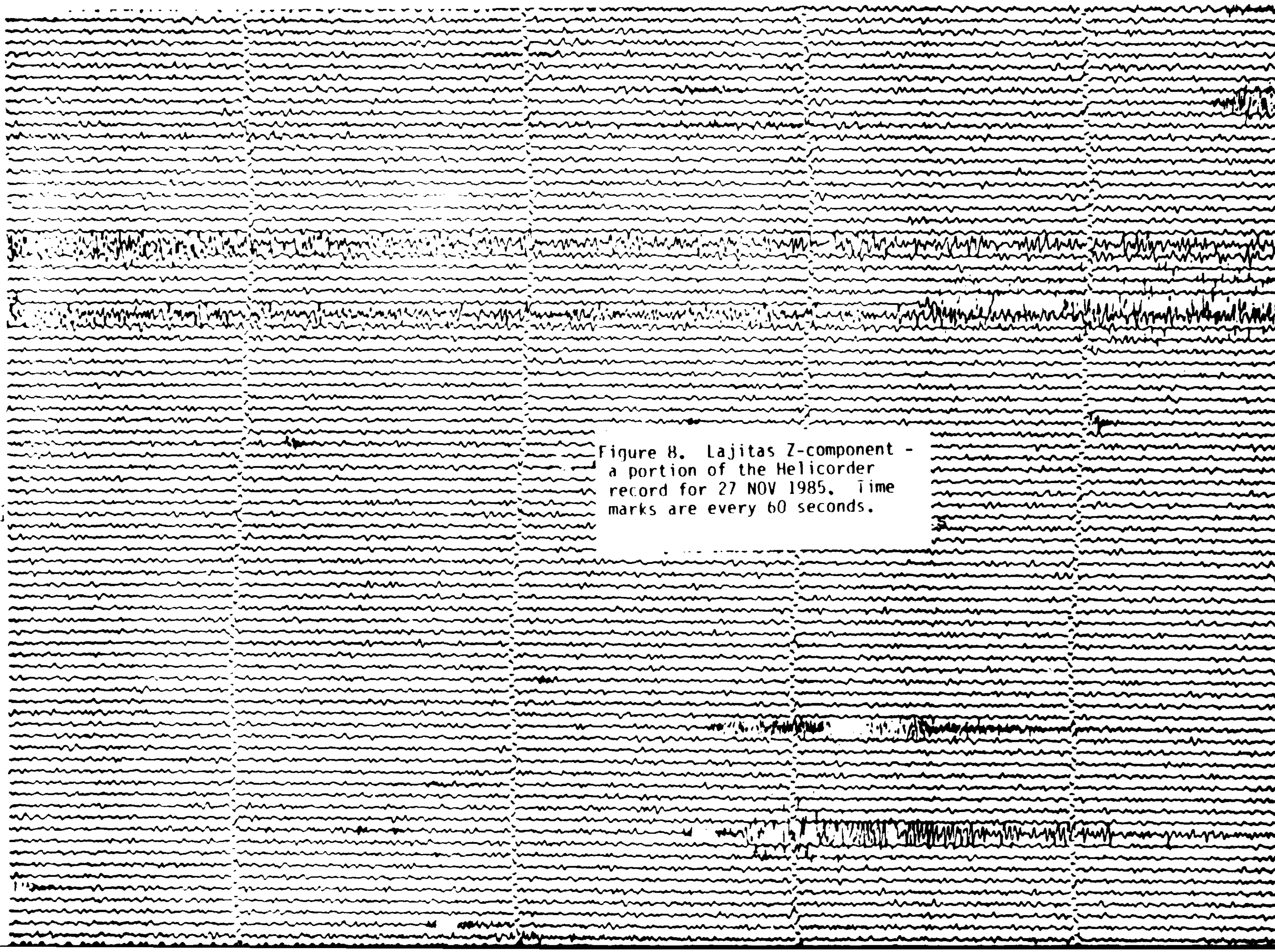

Figure 8. Lajitas Z-component - a portion of the Helicorder record for 27 NOV 1985. Time marks are every 60 seconds.

Conclusions

Noise measurements at Lajitas have shown it to be the quietest seismic station for which a consistent set of ambient noise measurements have been reported. As is true for all seismic stations, the background noise increases and thus the signal resolution drops with increasing wind velocity. Signal levels at Lajitas are somewhat above average based on observations during the GSETT recording period. Because of these properties, the Lajitas station has an excellent detection capability for local to teleseismic events.

PHASE ANALYSIS OF RAYLEIGH WAVES FROM THE SHAGAN RIVER TEST SITE IN THE USSR

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ABSTRACT

A study was made to determine if significant phase differences exist between Rayleigh waves which have traveled almost identical paths from the USSR Shagan River test site. Surface waves from five explosions recorded at six SRO/ASRO digital stations were used in the analysis. The explosion of 4 August 1979 was selected as a reference, and at each site the phase spectra of the Rayleigh waves from the other five events were compared to that of the reference. The technique of phase-matched filtering was used to analyze the signals. This technique reduces the effects of multipathing and removes phase differences due to dispersion along slightly different travel paths.

Each epicenter had been re-located by using calibration data from the cratering shot of 15 January 1965, and remaining errors in location and origin time are considered to be extremely small. Seismograms were analyzed for surface waves recorded at Matsushiro, Japan (MAJO); Shillong, India (SHIO); Kabul, Afghanistan (KAAO); Ankara, Turkey (ANTO); Grafenburg, W. Germany (GRFO); and Albuquerque, N.M. (ANMO).

Results of the study indicate that Rayleigh waves from some Shagan River explosions have undergone large phase shifts relative to Rayleigh waves which have traveled almost identical paths from other Shagan River explosions. In some cases, the phase shifts can be interpreted as complete phase reversals with associated time delays. In

particular, as compared to the explosion of 4 August 1979, Rayleigh waves from the explosion of 7 July 1979 are reversed in polarity at KAAO and ANTO and are reversed in polarity and delayed at CRFO, SHIO, and MAJO.

INTRODUCTION

One of the earliest conclusions from recordings of seismic surface waves from nuclear explosions was that Love waves, SH waves, and strongly asymmetrical Rayleigh radiation patterns were being generated by supposedly simple explosive sources. In more recent years other unexpected characteristics of explosion-generated surface waves have been observed. In particular, there have been observations of phase reversals (e.g., North and Fitch, 1981) and time delays (Von Seggern, 1973; Rygg, 1979) between Raleigh waves which have traveled almost identical paths from sites of nuclear explosions. Of these phenomena, all but the time delays have been explained to some extent as the result of a superposition of an explosion monopole and a double couple contribution from tectonic release (Harkrider, 1980; Archambeau, 1972). In order to use surface wave to determine the yields of nuclear explosions at the Shagan River Test Site, corrections for the non-isotropic effect must be made based upon an adequate model of the process. The model, such as the one proposed by Day et al (1986), must explain all of the observed phenomena including time delays.

It is extremely difficult to verify the existence of time delays (or, equivalently, linear phase differences as a function of frequency) between dispersed waves which have traveled slightly different paths. Relatively small errors in epicenter location and in origin time can introduce significant apparent phase changes, and improper corrections for dispersion for slightly different paths can also cause spurious phase shifts and time delays. Strong multipathing is often present and confuses the analysis. With these difficulties in mind, it is the objective of this study to determine if time delays exist, and if so, to measure them in as quantitative a way as possible. An effort has been made to utilize a data set which minimizes many of the errors associated with inaccurate locations and to utilize an analysis technique, phase-matched filtering, which seems particularly applicable to the problem.

DATA

Five presumed explosions were selected for study. Each occurred at the U.S.S.R. Eastern Kazakh test site in 1978 or 1979. Table 1 gives the origin time, latitude and longitude, and magnitude of each explosion. The indicated epicenters are the result of a re-location procedure accomplished by Lincoln Laboratories of the Massachusetts Institute of Technology (North and Fitch, 1981) using the cratering shot of 15 January 1965 (Nordyke, 1975) for calibration. The crater, the location of which is shown in Figure 1, has been positioned by satellite photography, and the resulting re-locations are thought to be accurate to within $\pm$ 3 km. The origin times shown in Table 1 were calculated during the location procedure and all are seen to be between 1.4 and 2.7 seconds before the even minute. The average travel time bias for the Eastern Kazakh source region has been estimated to be -2.3 seconds (Rodean, 1979). It is believed that these calculated origin times scatter about this bias, and that the true origin times are in every case almost exactly on the minute.

Figure 1 is a sketch map of the easternmost (Shagan River) portion of the Eastern Kazakh Test Site showing the locations of the five explosions. All five are in an area about 16 km by 10 km. Surface waves from these events were digitally recorded at the Seismic Research Observatories (SRO) and Abbreviated Seismic Research Observatories (ASRO) whose locations relative to the test site are shown in Figure 2. These stations are well-distributed in azimuth about the test site and range in distance from about 17° (1890 km) for

Kabul, Afghanistan (KAAO) to 95° (10,560 km) for Albuquerque, New Mexico (ANMO). The other stations are Matsushiro, Japan (MAJO); Shillong, India (SHIO); Ankara, Turkey (ANTO); and Grafenburg, W. Germany (GRFO). Digital data from other stations, such as CHTO, BCAO, KOND, etc., were not available for the reference event (4 August 1979).

PHASE-MATCHED FILTERING

A technique of phase-matched filtering (Herrin and Goforth, 1977, Goforth and Herrin, 1979) was used to analyze the data. A phase-matched filter (PMF) is a filter which has the same Fourier phase as one component of a composite signal, e.g., the same phase as the primary arrival in a multipathed seismic surface wave. Consider the synthetic, dispersed signal and the time domain representation of the phase-matched filter shown in Figure 3. The PMF has the same Fourier phase as the signal, but has a white amplitude spectrum in the frequency band 0.2 to 0.001 Hz. The cross-correlation of the two, shown in Figure 3, compresses the 600-second signal into a pulse of duration less than 100 seconds, approximately half the duration that would be achieved by correlation with a matched filter. Suppose the same synthetic signal is added to a second signal, producing the synthetic, multipathed signal as shown in Figure 4. The amplitude and phase of the original signal is now seriously distorted. Figure 5 demonstrates that if the multipathed signal is cross-correlated with the PMF, exactly the same correlation function results as was obtained without multipathing, except for the separate effect of the later arrival. A complete separation of the primary and multipath components is achieved in this synthetic example. The Fourier transform of a 100-second window centered at zero lag gives an excellent estimate of the amplitude spectrum of the primary arrival at frequencies greater than about 0.02 Hz; the phase of the primary arrival is the same as that of the PMF.

In practice the PMF must be derived from the multipathed signal. This is accomplished by first obtaining a group velocity dispersion function, $U(\omega)$, for the multipathed signal from a multiple filter analysis (Dziewonski, <u>et</u> <u>al</u>, 1969). Then the Fourier phase of a trial filter can be obtained from the group delay of the filter, tgr, by the relation

$$\theta(\omega_1) = \int_0^{\omega_1} t_{gr}(\omega)\, d\omega$$

where θ is the phase of the filter.

The correlation of the trial filter and the multipathed surface wave will result in a time series in which there are oscillations due to the phase mismatch of the trial filter and the primary signal and other oscillations due to multipaths. If the phase of the trial filter is sufficiently close to the phase of the primary signal at all frequencies and the arrival time differences between the primary and later arrivals are sufficiently large, the sets of oscillations can be separated, and the Fourier transform of a window excluding the multipath energy will yield a smoothed estimate of the phase correction needed. The trial filter is then updated and is correlated once again with the original multipathed signal, and the process is repeated until the phase error is zero. Thus a phase-matched filter is obtained. By this process the amplitude and phase of the unmultipathed portion of the signal can be determined.

DATA ANALYSIS

The diversity of the Rayleigh waveforms resulting from the 5 explosions can be seen in Figure 6, where the arrivals at Kabul, Afghanistan, are shown. The waveforms from the 4 August 1979 and 23 June 1979 events are similar, but the 7 July 1979 Rayleigh wave is characterized by prominent long-period (T=40 to 50 seconds) energy and the appearance of being reversed in phase. The 4 November 1978 Rayleigh wave is similar to that of the 7 July 1979, event while the 15 September 1978 Rayleigh shows large amplitudes preceding the fundamental mode arrival. The Rayleigh arrivals at the other stations are similarly diverse. Since Rayleigh waves from the explosions have traveled almost identical paths to Kabul, the differences in the waveforms are presumably due to differences at the source. In order to determine the amplitude and phase differences between the Rayleigh arrivals at each station, the following procedure was undertaken. A PMF was obtained for the primary Rayleigh arrivals at each of the six SRO/ASRO stations for the explosion of 4 August 1979. The PMF's for this reference event, adjusted for the appropriate distances, were applied to the Rayleigh waves at each station for each of the other four events. The Fourier transforms of the resulting windowed correlations provided the spectral phase difference between the unmultipathed portions of the reference event and each of the others.

As an example of this procedure, consider Figure 7 which shows the Rayleigh arrivals at Albuquerque, New Mexico, from the 4 August 1979 event, which was chosen as the reference, and the 23 June 1979 event. The waves have been well dispersed over the 95° travel path, and any differences in amplitude or phase are not immediately obvious. A PMF was found for the reference event, and on the final iteration the correlation of the PMF with the signal produced the first correlation function shown in Figure 7. The same filter, adjusted for the dispersion over the 1 km difference in distance, was applied to the 23 June 1979 event, producing the second correlation function in Figure 7. The phase of this correlation function is the difference in phase between the two primary signals. The Fourier transform of a 100-second window centered at zero lag gives an estimate of the phase difference between the unmultipathed portions of the two signals. In Figure 8 the phase difference is plotted as a function of frequency. A maximum phase difference of only about 10° at a frequency of .03 Hz is seen in this plot. A near-linear plot of this type can be interpreted in terms of the slope of a first order trend (a time delay/advance) and a zero-frequency intercept (an all-pass phase shift). The data in Figure 8 has a linear trend with slope between zero and 1 sec and with a zero-frequency intercept less than 10°. The resolution of the phase-matching technique is limited by the 1 sps sampling rate of the data to about 10° at mid-band and a similar amount in the estimate of the zero-frequency intercept. The analysis therefore indicates no significant phase differences nor any significant time delay between the two signals.

As another example of the analysis procedure, consider Figure 9 which shows the Rayleigh arrivals at Ankara, Turkey, from the 4 August 1979 event and the 15 September 1978 event. The waveforms show strong multipathing. A PMF was determined for the 4 August 1979 reference event, and on the final iteration the correlation of the PMF with the signal produced a correlation function of which the windowed portion is shown in Figure 9. The application of the PMF to the 15 September 1978 event gives the second windowed correlation function, the Fourier transform of which yields the phase difference between the unmultipathed portions of the two signals. This phase difference is plotted in Figure 10. Again, the slope of the linear trend is less than the 1 second sampling interval; phase differences do not exceed about 10^{o} at any frequency, including the zero-frequency intercept. There is, therefore, no significant phase difference or time shift between the two signals. The uncertainties introduced by strong multipath modulation have been eliminated by phase-matched filtering.

The majority of the Rayleigh waves analyzed showed no significant phase differences or time shifts relative to the reference event. However, of the 30 waveforms studied, 8 were determined to be anomalous either in terms of significant phase shifts, time delays, or both. The event of 7 July 1979 proved to be anomolous at all of the stations. The 4 November 1979 Rayleigh arrivals at MAJO and SHIO and the 15 September 1978 Rayleigh arrival at SHIO were also anomalous.

The Rayleigh waves from the 4 August 1979 reference event and the 7 July 1979 event as recorded at Matsushiro, Japan, are shown in Figure 11. The 7 July 1979 correlation function produced by the filtering process is obviously upside down relative to that of the reference event. The Fourier transform of the windowed correlation function in Figure 11 provides the phase difference between the two signals which is plotted as a function of frequency in Figure 12. The plot shows a zero-frequency intercept near 180 verifying the polarity reversal, but it also shows a strong linear trend with a slope of 3.2 seconds. Therefore, the 7 July 1979 Rayleigh arrival as observed at MAJO is reversed in polarity and delayed by approximately 3 seconds relative to the 4 August 1979 Rayleigh arrival. Rayleigh waves from the 7 July 1979 explosion were also reversed in polarity and delayed relative to the reference event at Grafenberg (delay = 2.4 sec) and Shillong (delay = 9.8 sec). The result at Shillong is particularly interesting because of the large indicated delay and the presence of an interfering event. The Rayleigh seismograms for the events of 4 August 1979, 7 July 1979, and 23 June 1979 are shown in Figure 13 along with the corresponding correlation functions resulting from phase matched filtering. The Rayleigh waves are not well dispersed over the short travel path and appear almost pulse-like. Both the seismograms and the correlation functions for the reference and 23 June 1979 events are almost identical, while the 7 July 1979 Rayleigh wave is very different, being low-level and distorted by an interfering event. The phase analysis of the 7 July 1979 correlation is shown in Figure 14. A strong linear trend indicates almost a 10-second delay and a polarity reversal relative to the reference. Phase-matched filtering of the 7 July 1979 Rayleigh waves at Kabul, Afghanistan, and Ankara, Turkey, showed no time delays but revealed all-pass phase shifts, relative to the reference event, of about 220°. No analysis was possible for the Rayleigh arrival for this event at Albuquerque because of poor signal-to-noise ratio.

Figure 15 summarizes the results for the Rayleigh waves for the 7 July 1979 event. In this figure the spectral amplitudes at a period of 25 sec relative to that of the reference event are plotted for the 7 July 1979 event. The amplitude ratio is expressed in dB at each station, with positive dB meaning that the 7 July 1979 amplitude is larger than that of the reference event. There is a 30 dB swing with azimuth, with the amplitude at Kabul 12 dB greater than the reference and the amplitude at Shillong 18 dB less. There is a definite trend of higher amplitudes for the 7 July event in a SW-NE line, and low amplitudes in NW-SE direction. The very low amplitudes at Shillong and Grafenberg were accompanied by time delays and 180° phase reversals. The arrivals with higher amplitudes at Kabul and Ankara showed no time delays and the frequency-independent phase shift appeared to be more like 220 degrees than 180. But this pattern was broken at Matsushiro where a substantial amplitude was accompanied by a 3-sec time delay and the phase reversal was 180°.

In addition to the anomolous event of 7 July 1979, there were three other instances of unusual Rayleigh waves in the data set studied. Their phases relative to the reference are shown in Figure 16. The 4 November 1978 Rayleigh arrival at KAAO looks very much like the 7 July Rayleigh arrivals at Kabul and Ankara. The phases of the other two, 4 November 1978 at MAJO and 15 September 1978 at SHIO, have a non-linear frequency dependence that is not easily interpreted in terms of a slope and intercept. Nevertheless, there appear to be in both cases first order trends equivalent to 3 to 4 second time delays.

DISCUSSION

The majority of the Rayleigh waves studied showed amplitude and phase characteristics which are consistent with an explosive source in an isotropic medium. The explosion of 7 July 1979 is an exception in that it generated Rayleigh waves which were approximately reversed in polarity at all recording stations. Theoretically, a polarity reversal at all azimuths could be produced by a strong [illegible] contribution from thrust-like tectonic release; however, two other characteristics of the 7 July 1979 explosion which were determined in the present analysis have not yet been explained. These are the all-pass phase shifts of 220° (rather than 180°), and the time delays at some azimuths. Of principal interest are the time delays. Apparent time shifts can be generated by a variety of errors and improper data adjustments such as errors in epicenter location, errors in origin times, improper corrections for dispersion over slightly different paths, and improper interpretation of the slope of the first order trend of the phase vs frequency curve because of limited bandwidth and resolution. It is of interest to consider the possible effects of each of these sources of error on the results.

The epicenters of the explosions are thought to be very accurate because they were adjusted to the location of the cratering shot of [illegible] January 1965. Nevertheless, location errors of ± 3 km could result in a travel time error of approximately ± 1 second. In the worst case, where the reference event might be mis-located by 3 km and one of the other events mis-located by 3 km in the opposite direction, spurious time shift of about 2 seconds would be introduced in certain directions. However, in one direction the spurious time shift would be a delay and in the other direction an advance. There would be no time shift in directions perpendicular to a line parallel to the direction of location error. Thus the effect of the worst case of epicenter location error would be to introduce an azimuthally alternating pattern of advances and delays with maximum value of about 2 seconds. As shown in Figure 2, the recording stations from which seismograms were analyzed are well-distributed in azimuth and such a pattern would be easily recognized. In fact, the time shifts observed for the explosion of 7 July 197[illegible] were all delays relative to the reference event.

The origin times of the explosions are thought to be extremely accurate. During the 1978-1979 period which includes the set of explosions used in this study the USSR very likely followed the practice of the U.S. and France and detonated all their nuclear tests within one or two tenths of a second after the minute. The study of Rodean (1979) supports this conclusion. In any case, a relative error in origin time between the reference event and one of the other events of, say, ± [illegible] seconds would result in time delays or advances of [illegible] seconds at all azimuths. Again, this was not observed.

Adjustments for phase changes due to dispersion over slightly different path lengths was accomplished in the phase matched filtering analysis by utilizing the dispersion curve for the entire travel path. For example, the distance from the 4 August 1979 epicenter to Kabul, Afghanistan, is 1887 km, while the distance from the 4 November 197[illegible] epicenter to Kabul is [illegible] km, a difference of [illegible] km. The difference in phase due to the 16 km difference in travel path was calculated on the basis of the average dispersion observed over the entire Shagan River-Kabul travel path. Ideally, the correction should be based on the dispersion curve for the test site, but this is not known. The procedure used in this analysis could introduce a slight error that increases with the difference between the average dispersion over the total path and the dispersion on the test site, and with increasing difference in path length between the reference event and the others. The 16 km path length difference to Kabul represents a worst case in both categories; however, no time shift was observed between the 4 August 1979 and 4 November 1978 Rayleigh waves at Kabul.

By calculating the spectral phase difference from the Fourier transform of a 100-sec window, the effects of multipaths were eliminated. However, the narrow window reduced the frequency resolution of the spectral estimates to 0.01 Hz, so that only 5 independent spectral estimates were obtained in the pass band 0.02 to 0.06 Hz. The additional points that appear in the various phase vs frequency plots are interpolations obtained by zero-filling the transform window to a total of 1024 points. Nevertheless, the 5 independent estimates in the pass band are consistent with a systematic trend, and the interpolated points serve to define the trend of the curve visually. No significant error in determining the slope of the first order trend is thought to be introduced by the relatively poor frequency resolution.

The model of tectonic release proposed by Day et al. (1986) predicts that linear phase shifts (time delays) can be produced, particularly in propagation directions where the Rayleigh waves from the explosions and the reversed Rayleigh waves from the tectonic release are of similar size. In this study we found that the largest time delays occurred in directions where the Rayleigh waves were weakest as would be predicted by the model of Day et al. (1986).

CONCLUSIONS

The analysis of digital Rayleigh wave seismograms at six SRO/ASRO seismic stations from five explosions at the USSR Shagan River nuclear test site indicates that five of the Rayleigh arrivals are reversed in polarity and delayed relative to a reference event. Since the Rayleigh waves have traveled almost identical paths from the various explosion sites to each station, the polarity reversals and time delays are presumed to be due to source effects. These effects appear to be explained by the model proposed by Day et al. (1986).

ACKNOWLEDGMENTS

Funds for this research were provided by the Defense Advanced Research Projects Agency under Contract AFOSR F49620-81-C-0010 monitored by the U.S. Air Force Office of Scientific Research and Contract AFSC F 19628-85-K-0032 monitored by the Air Force Geophysics Laboratory. Many of the computations were performed by Bijan Rafipour and Nancy Cunningham.

REFERENCES

Archambeau, C. B., 1972, The theory of stress wave radiation from explosions in pre-stressed media, Geophys. J. R. Astr. Soc., v. 29, pp. 329-366.

Day, Steven M., J. T. Cherry, Norton Rimer, and J. L. Stevens, 1986, Nonlinear model of tectonic release from underground explosions, submitted to Bull. Seis. Soc. Amer.

Dziewonski, A. M., S. Bloch, and M. Landisman, 1969, A technique for the analysis of transient seismic signals, Bull. Seis. Soc. Amer., v. 59, pp. 427-444.

Goforth, Tom and Eugene Herrin, 1979, Phase-matched filters: Application to the study of Love waves, Bull. Seis. Soc. Amer., v. 69, pp. 27-44.

Harkrider, D. G., 1980, Coupling near source phenomena into surface wave generation, Proc. of NATO Advanced Study Institute on Identification of Seismic Sources, Oslo, Norway, Sept. 1980, D. Reidel Pub. Co., Dortrecht, The Netherlands.

Herrin, Eugene and Tom Goforth, 1977, Phase-matched filters: Application to the study of Rayleigh waves, Bull. Seis. Soc. Amer., v. 67, p. 1259-1275.

Nordyke, M. D., 1975, A review of Soviet data on the peaceful uses of nuclear explosions, Annals of Nuclear Energy, v. 2, pp. 657-673.

North, R. G. and T. J. Fitch, 1981, Surface wave generation by underground nuclear explosions, Unpublished manuscript

Rodean, .H. C., 1979, ISC origin times for announced and presumed underground nuclear explosions at several test sites, Lawrence Livermore Laboratory document, UCRL-52882, 22p.

Rygg, E., 1979, Anomalous surface waves from underground explosions, Bull. Seis. Soc. Am., v. 69, pp. 1995-2002.

Von Seggern, D. H., 1973, Seismic surface waves from Amchitka Island Test Site events and their relation to source mechanism, Jour. Geophys. Res., v. 78, pp. 2467-2474.

Table 1. Explosions at Shagan River for which surface waves were analyzed.

EVENT	ORIGIN TIME		LAT° N	LONG° E	M_b
9	9/15/78	02:36:57.3	49.923	78.842	6.0
10	11/04/78	05:05:58.1	50.027	78.921	5.5
12	6/23/79	02:56:58.6	49.894	78.828	6.2
13	7/07/79	03:46:58.3	50.001	78.958	5.8
14	4/08/79	03:56:58.0	49.904	78.843	6.0

Figure Captions

FIGURE 1 — Sketch map of the easternmost (Shagan River) portion of the Eastern Kazakh Test Site showing the locations of the five explosions selected for study (event numbers can be referenced to Table 1).

FIGURE 2 — Plot showing the location of the ASRO/SRO stations relative to the Shagan River testing area.

FIGURE 3 — Synthetic signal (top trace); time domain representation of the filter (middle trace); and the cross-correlation of the two upper traces.

FIGURE 4 — Synthetic dispersed signal (top trace) interfering signal (middle trace), and synthetic multipathed signal formed by summing the first two traces (lower trace).

FIGURE 5 — Synthetic multipathed signal (top trace), the phase-matched filter (middle trace), and the cross-correlation (lower trace).

FIGURE 6 — Rayleigh waveforms resulting from 5 explosions recorded at Kabul, Afghanistan.

FIGURE 7 — Rayleigh arrivals at Albuquerque, New Mexico, from the 4 August 1979 event, and the 23 June 1979 event, and their correlation functions.

FIGURE 8 — Phase of 23 June 1979 Rayleigh relative to 4 August 1979 Rayleigh as determined at Albuquerque by phase-matched filtering.

FIGURE 9 — Rayleigh arrivals at Ankara, Turkey, from the 4 August 1979 event and the 15 September 1978 event.

FIGURE 10 — Phase of 15 September 1978 Rayleigh arrival relative to 4 August 1979 arrival as determined at Ankara by phase-matched filtering.

FIGURE 11 — The Rayleigh waves from the 4 August 1979 reference event and the 7 July 1979 event as recorded at Matsushiro, Japan, and their windowed correlations produced by phase-matched filtering.

FIGURE 12 — Phase of 7 July 1979 Rayleigh relative to 4 August 1979 Rayleigh as determined at Matsushiro by phase-matched filtering.

FIGURE 13 — The Rayleigh seismograms for the events of 4 August 1979, 7 July 1979, and 23 June 1979, as recorded at Shillong, India, and their corresponding correlation functions resulting from phase-matched filtering.

FIGURE 14 — Phase of 7 July 1979 Rayleigh relative to 4 August 1979 Rayleigh as determined at Shillong by phase-matched filtering.

FIGURE 15 — Spectral amplitude, at 25 second period, of Rayleigh waves from the 7 July 1979 event relative to the reference event (4 August 1979).

FIGURE 16 — Phase of 4 November 1978 Rayleigh arrivals at MAJO and KAAO, and the 15 September 1978 Rayleigh arrival at SHIO relative to the reference event as determined by phase-matched filtering.

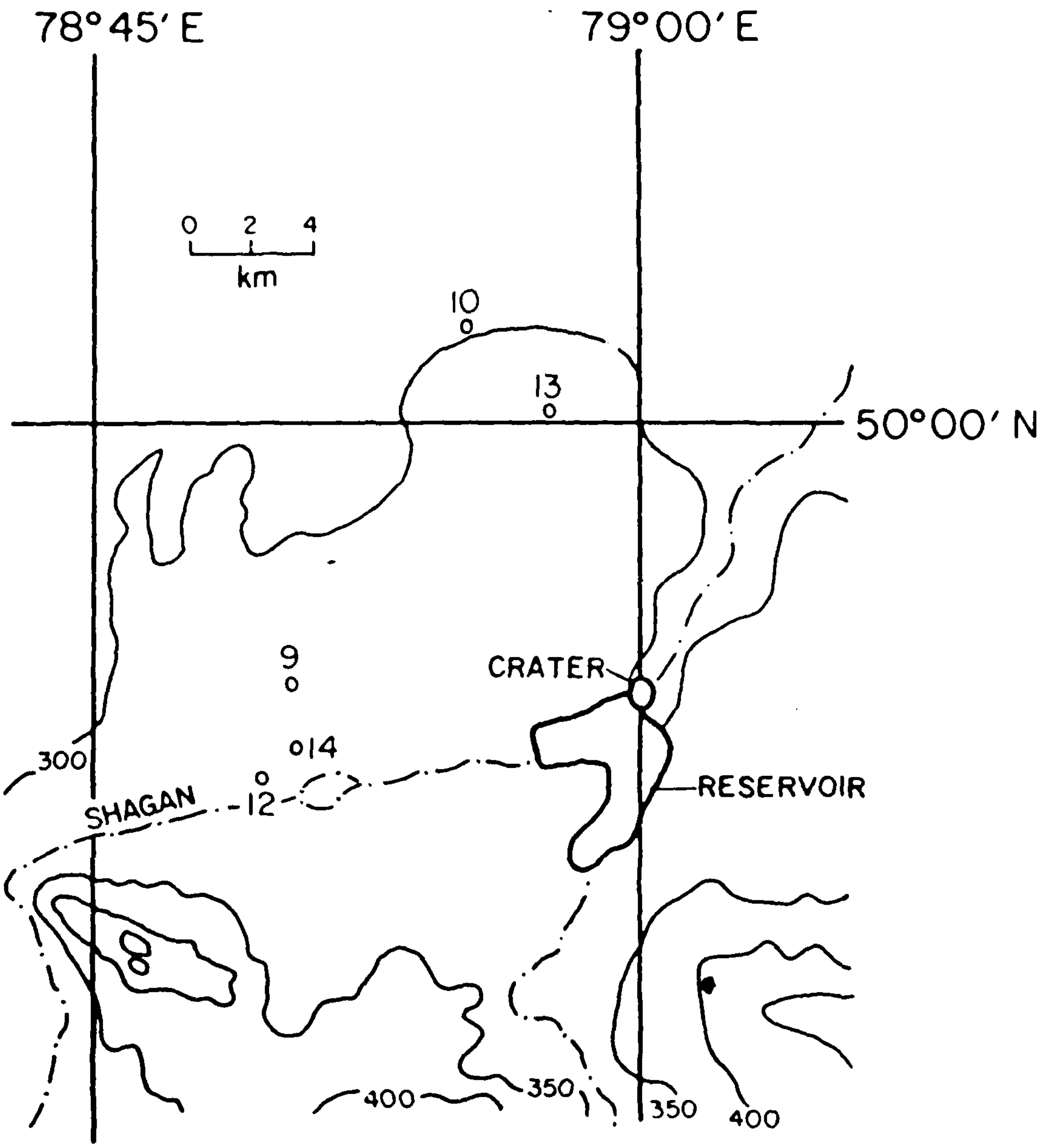
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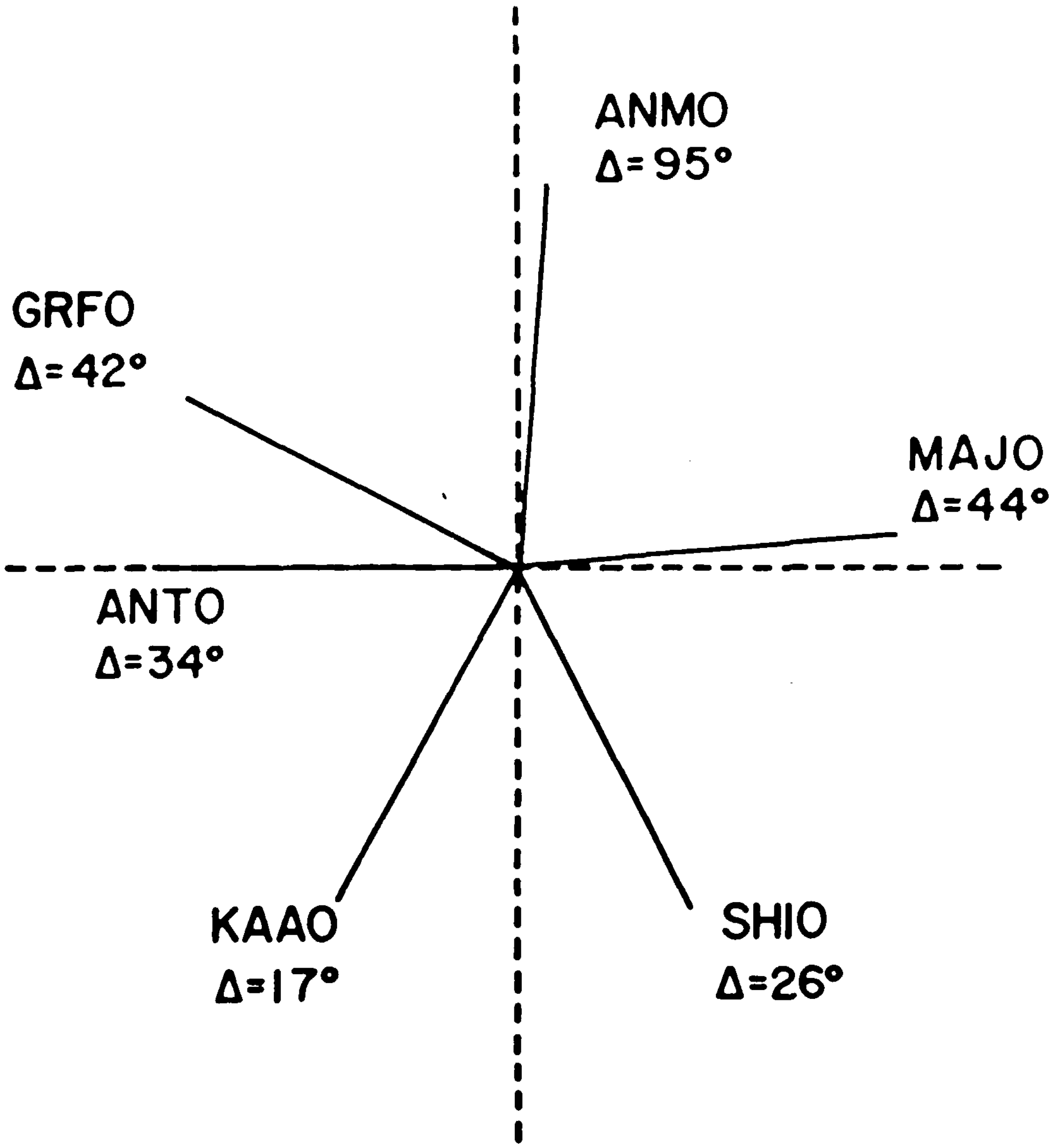
Figure 1



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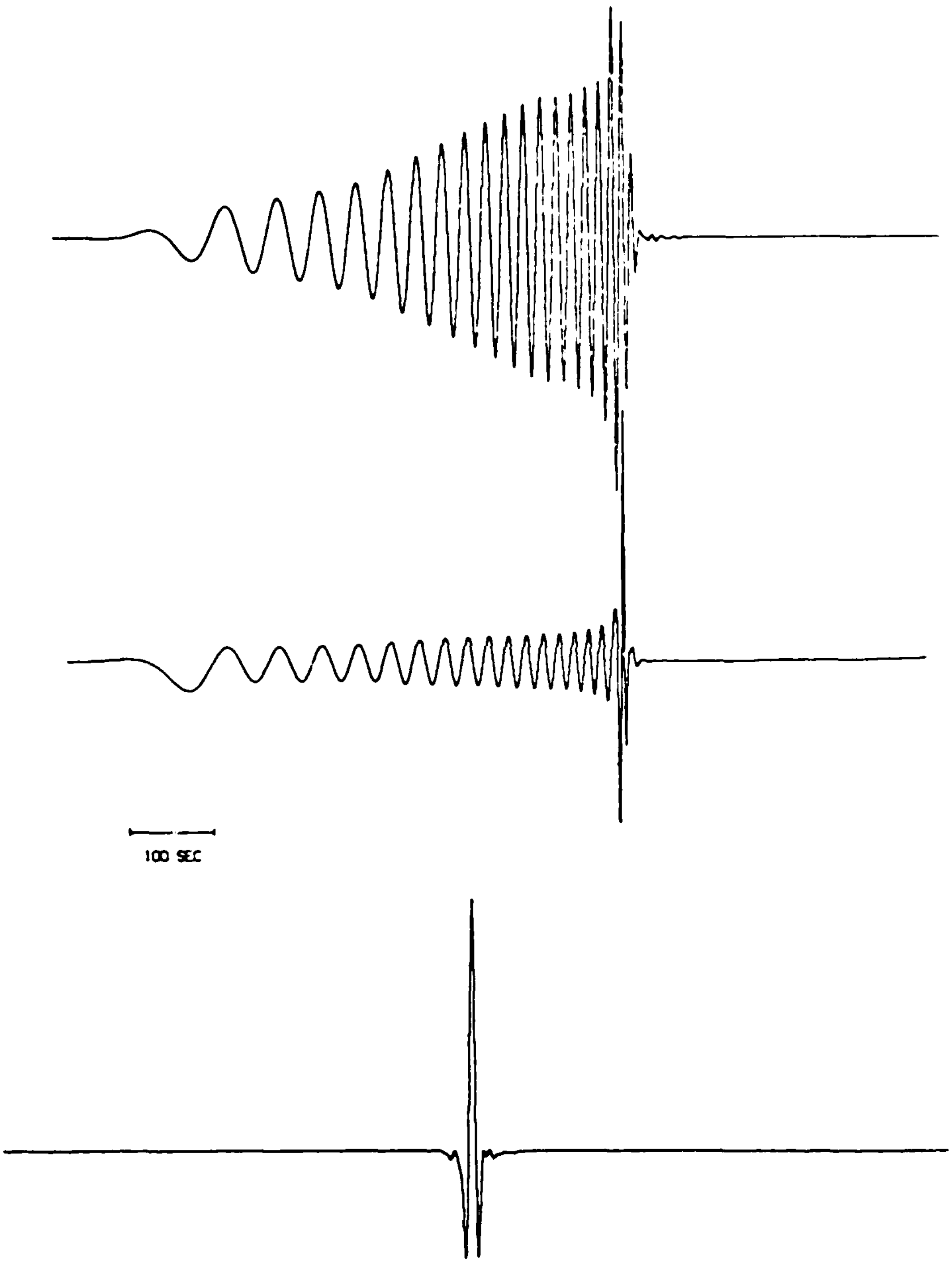

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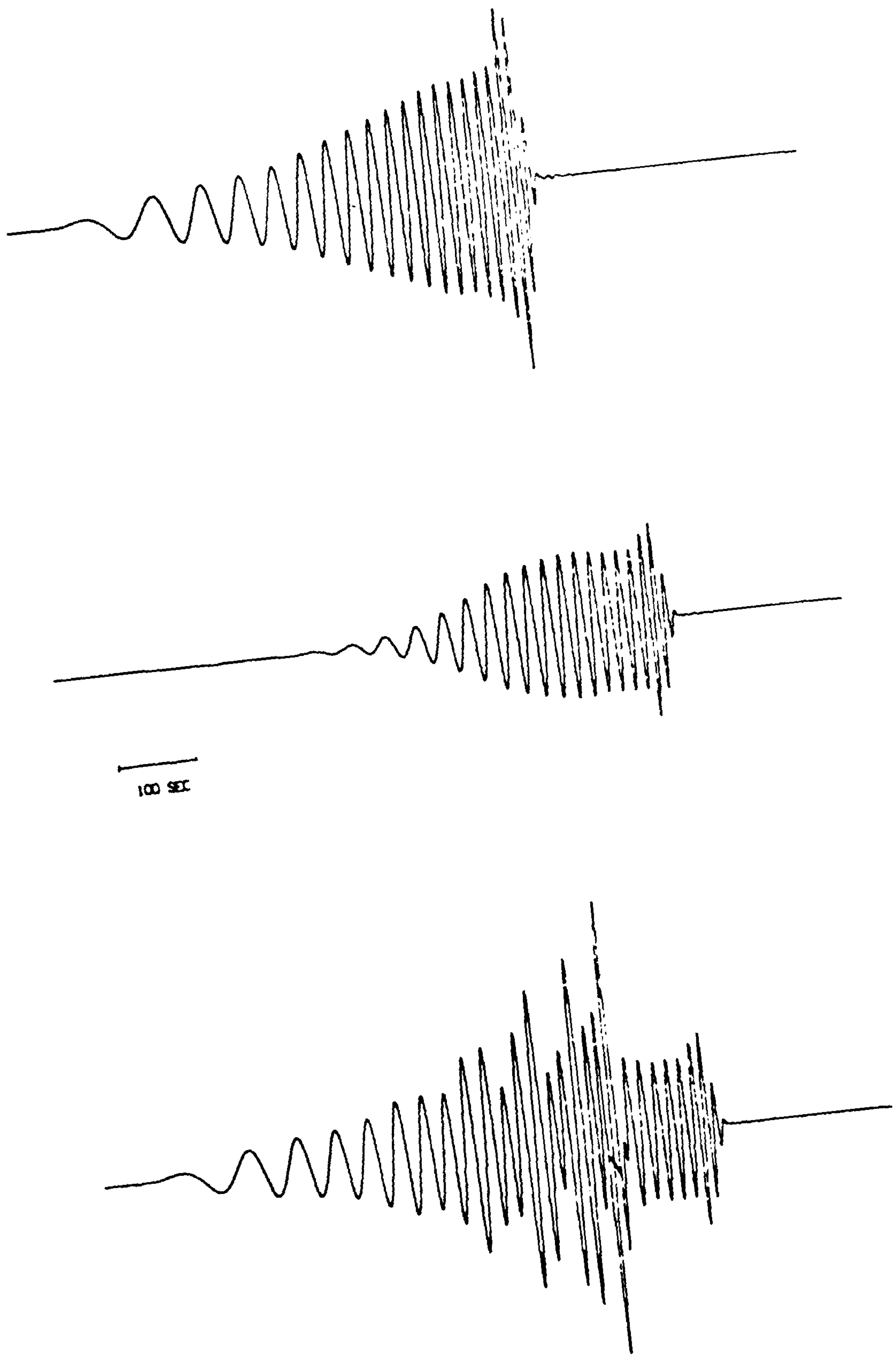

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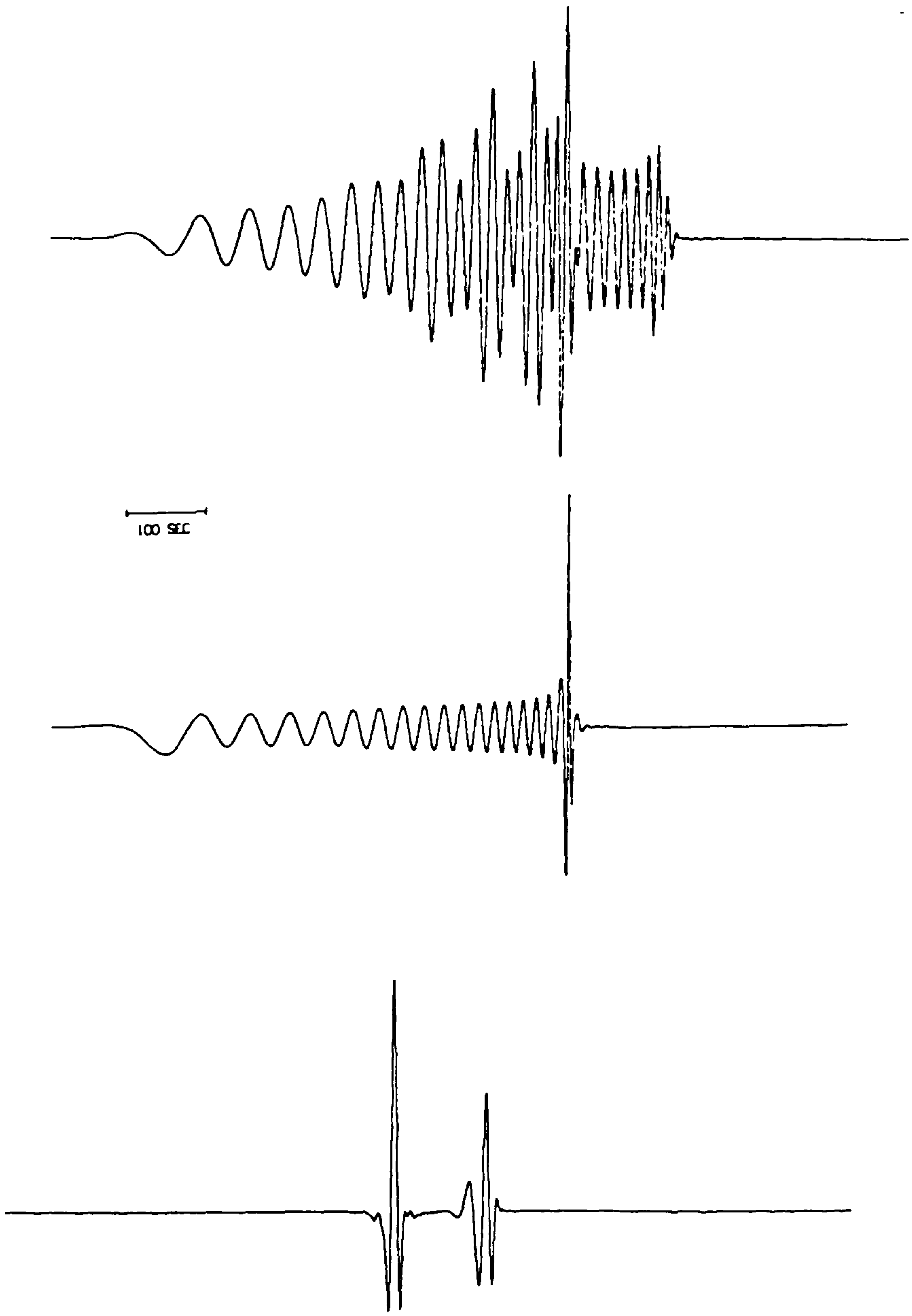

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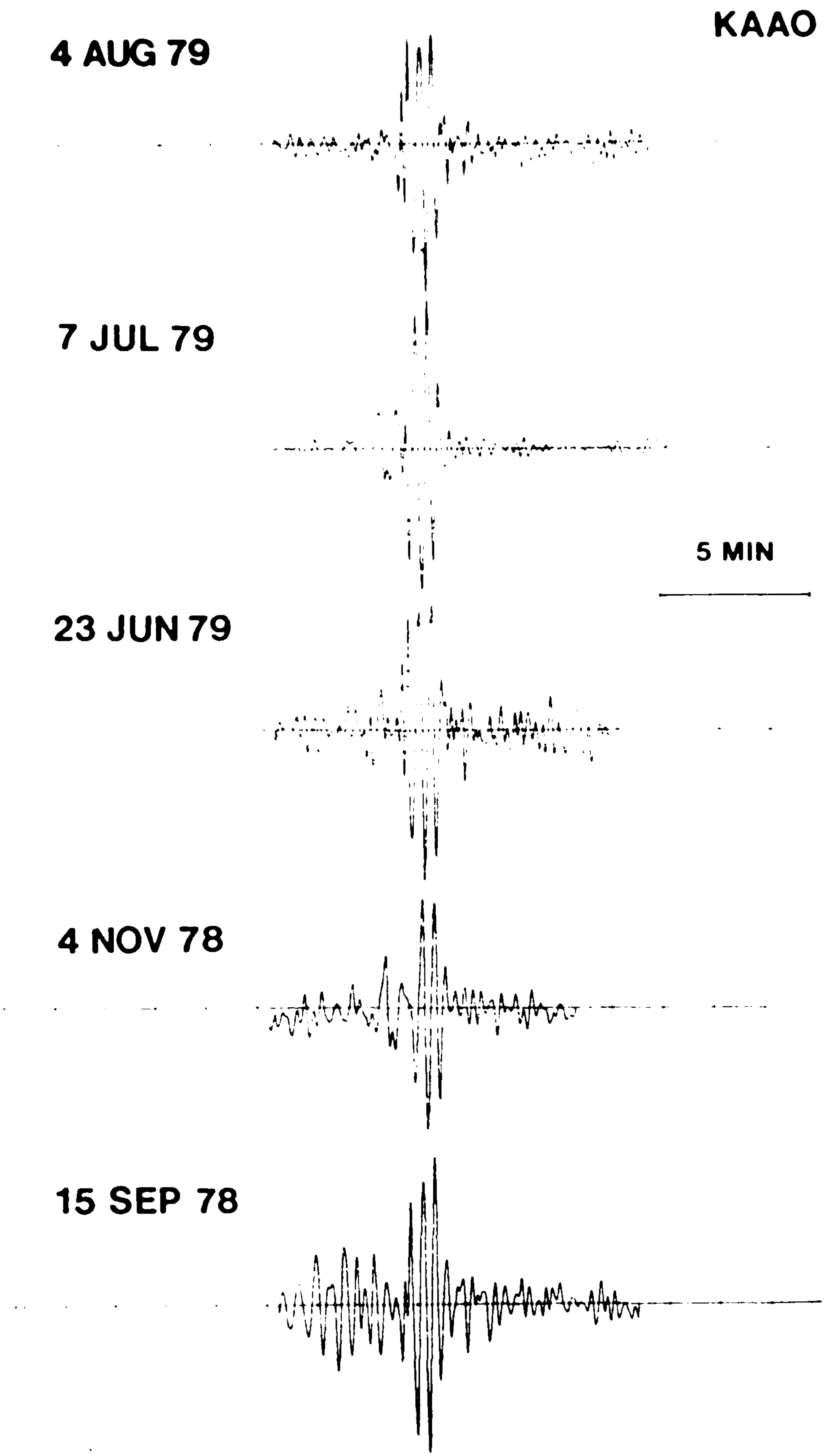

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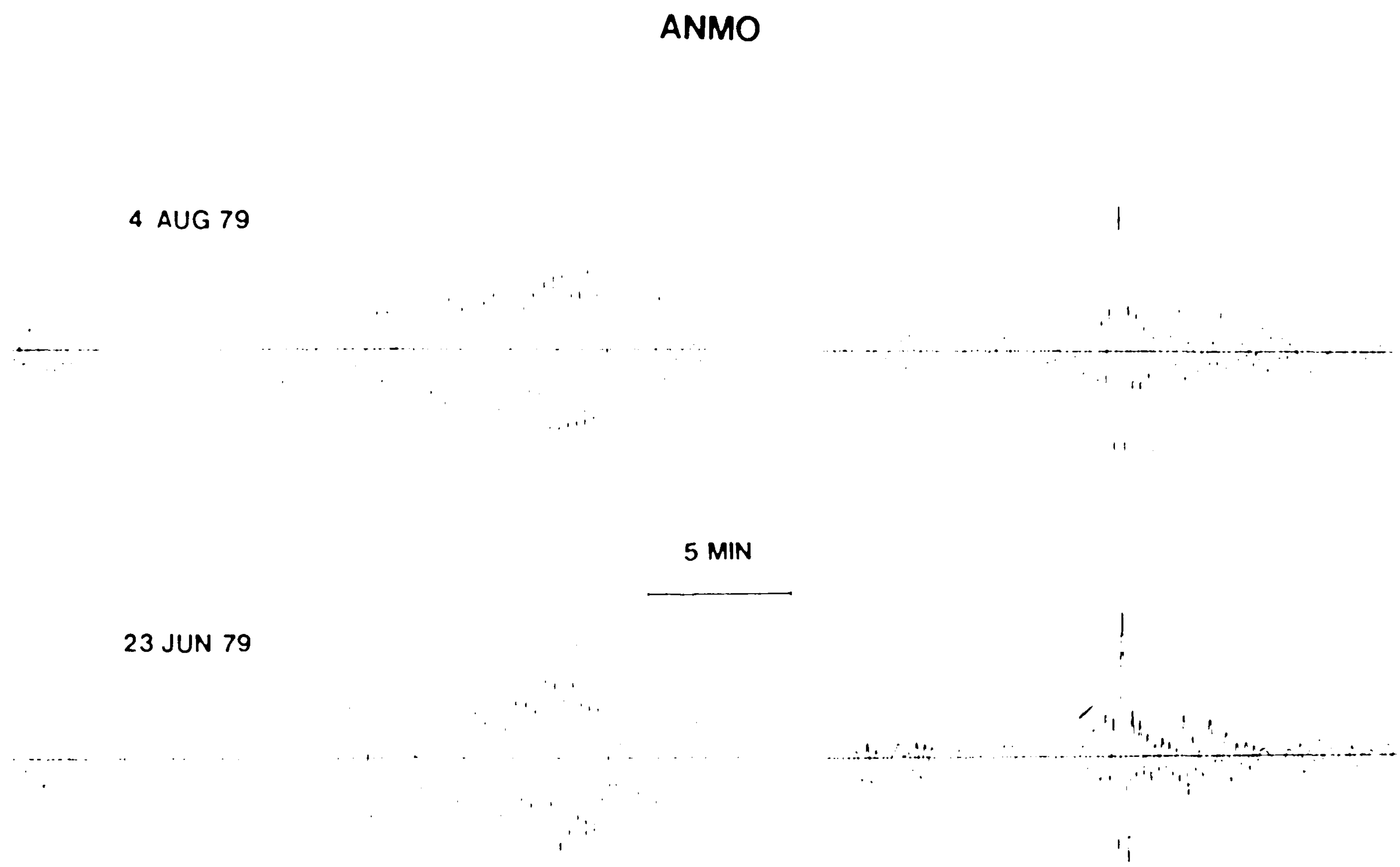
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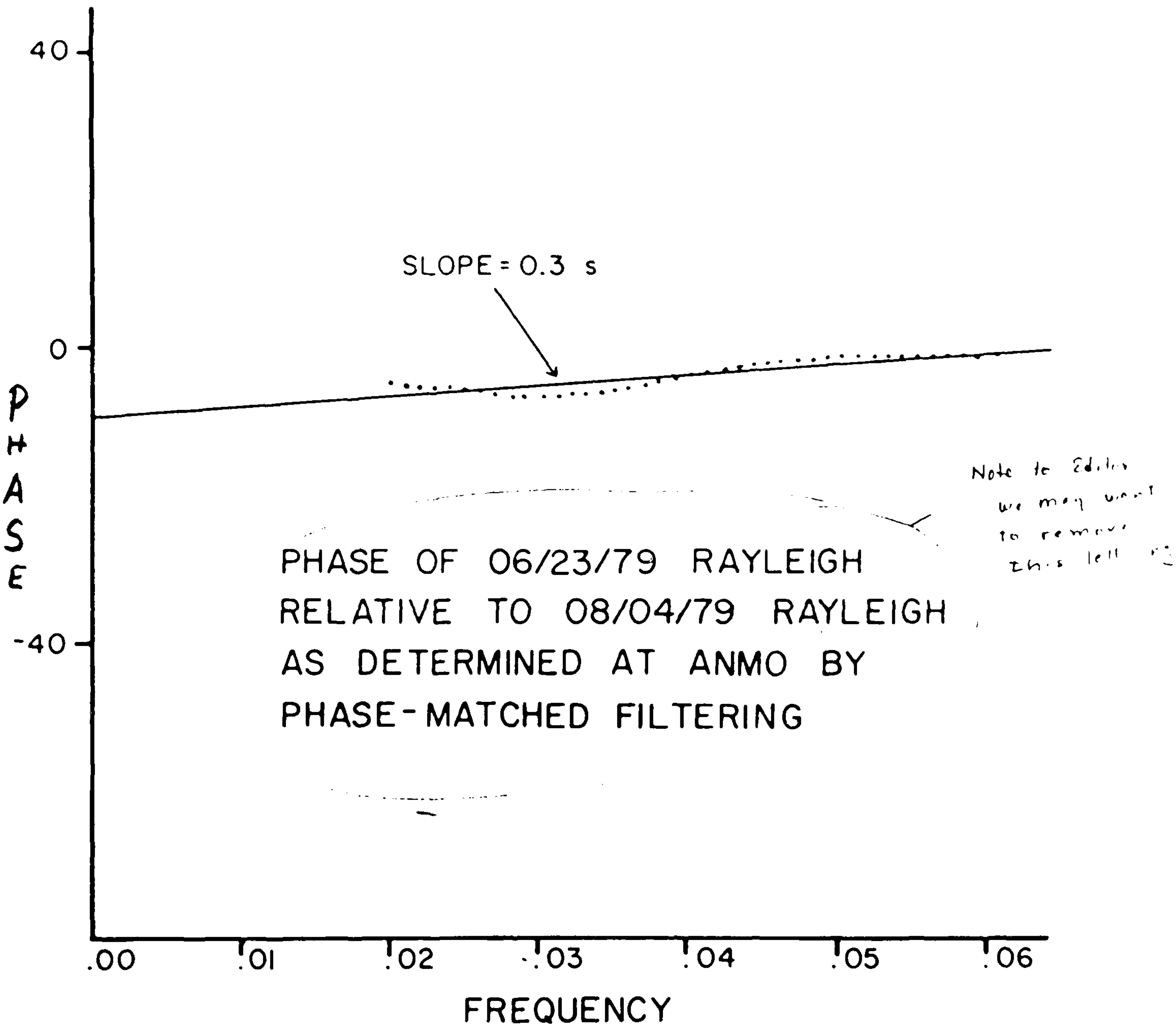
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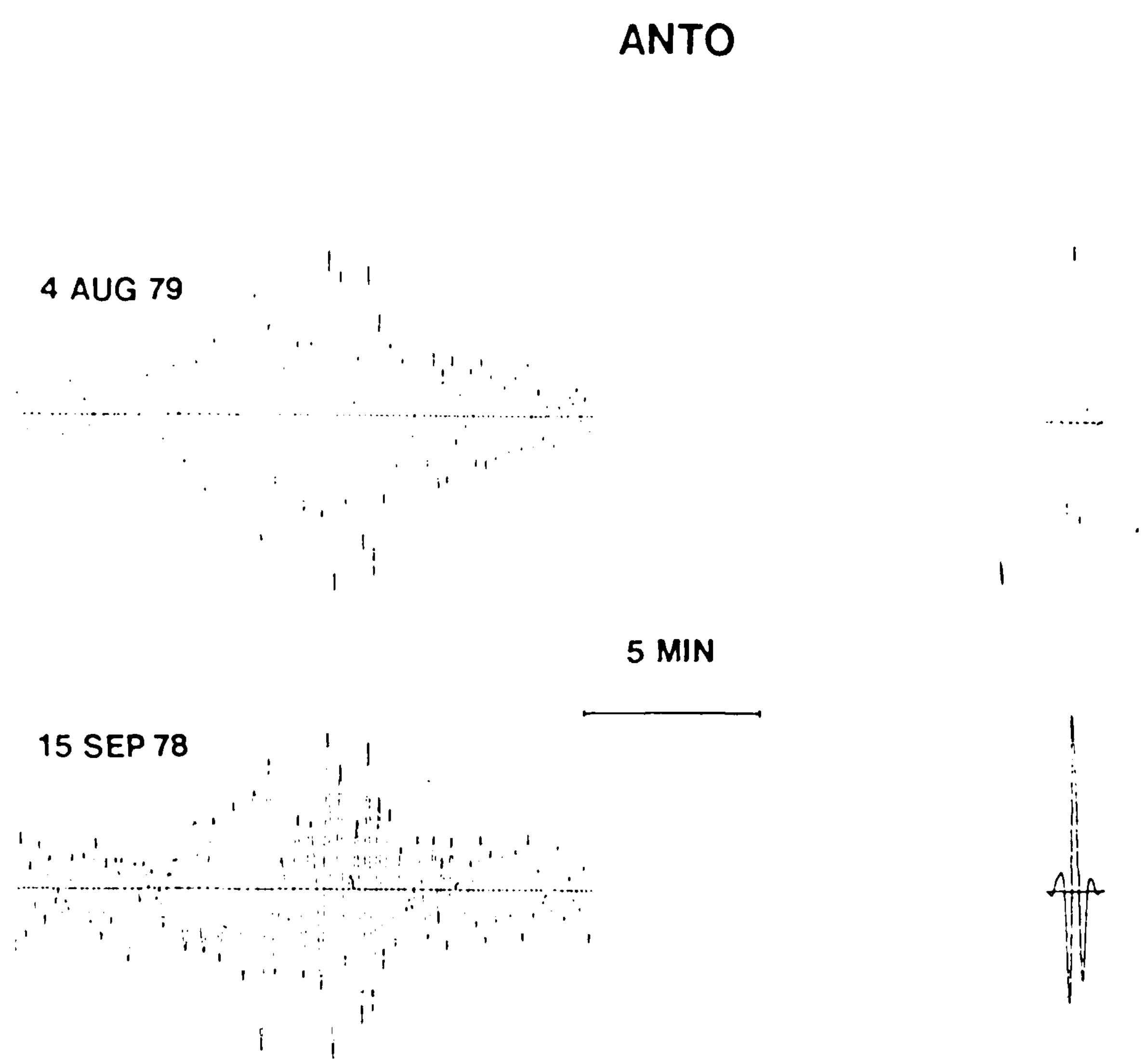

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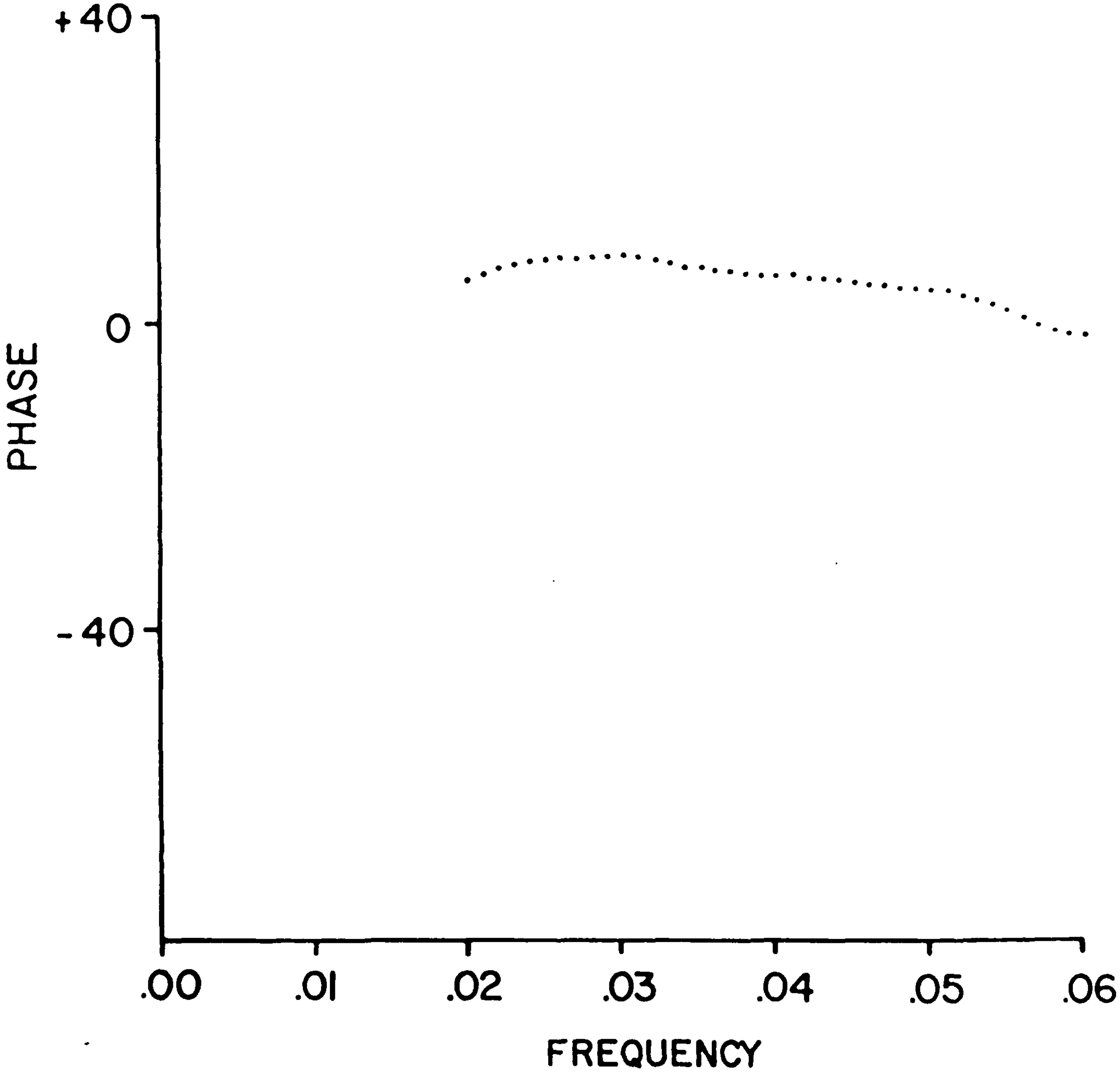

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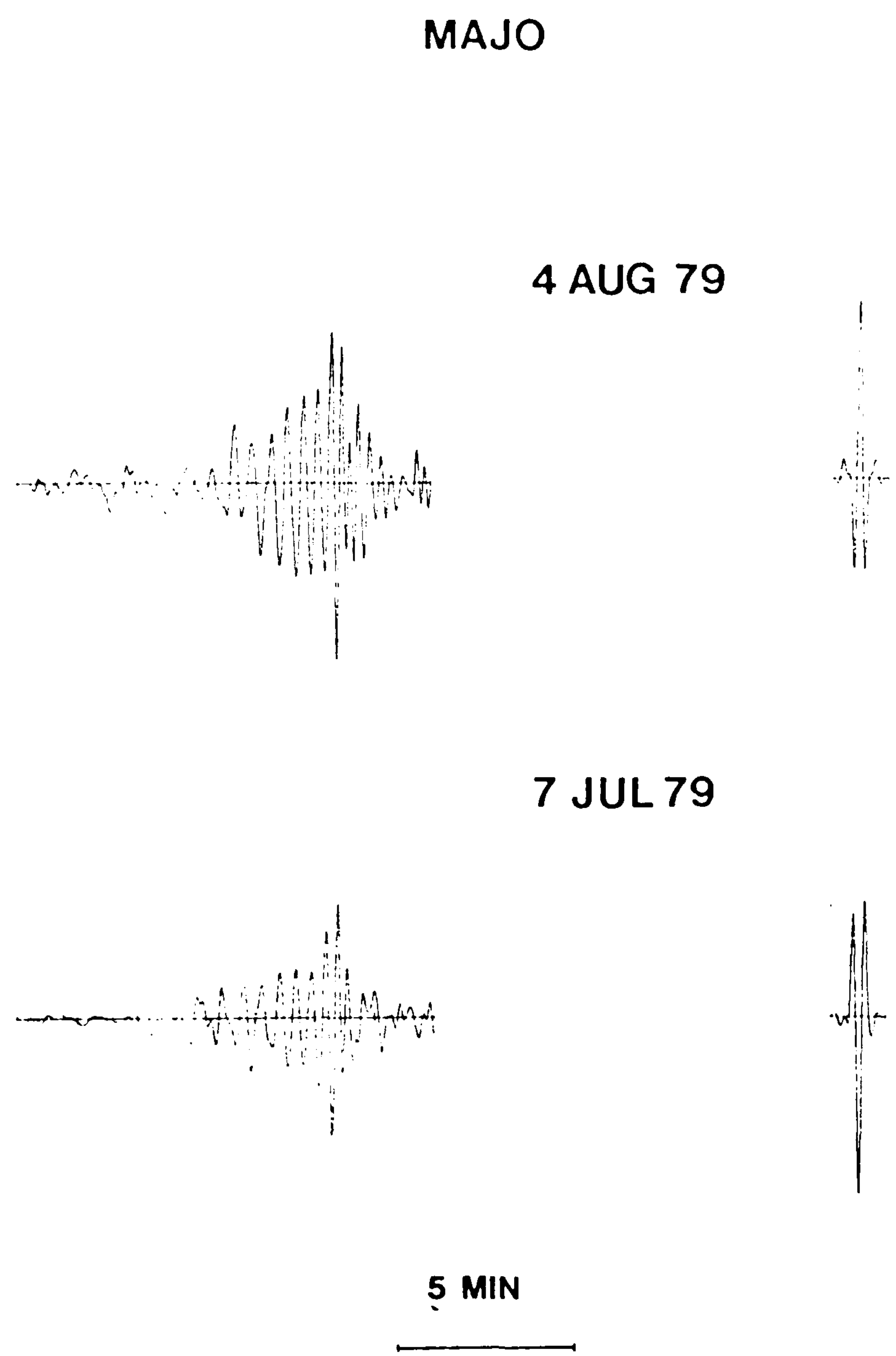

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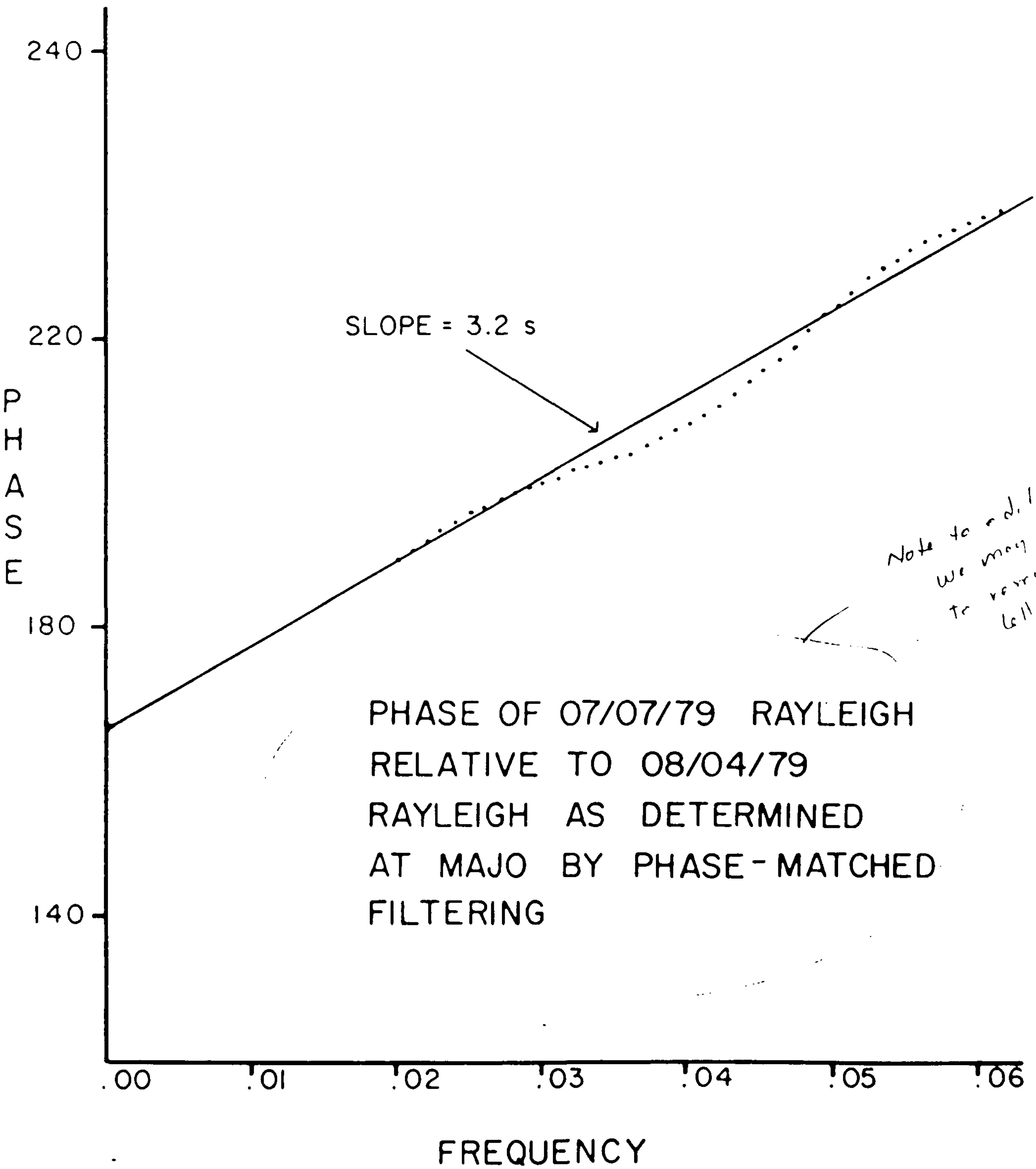
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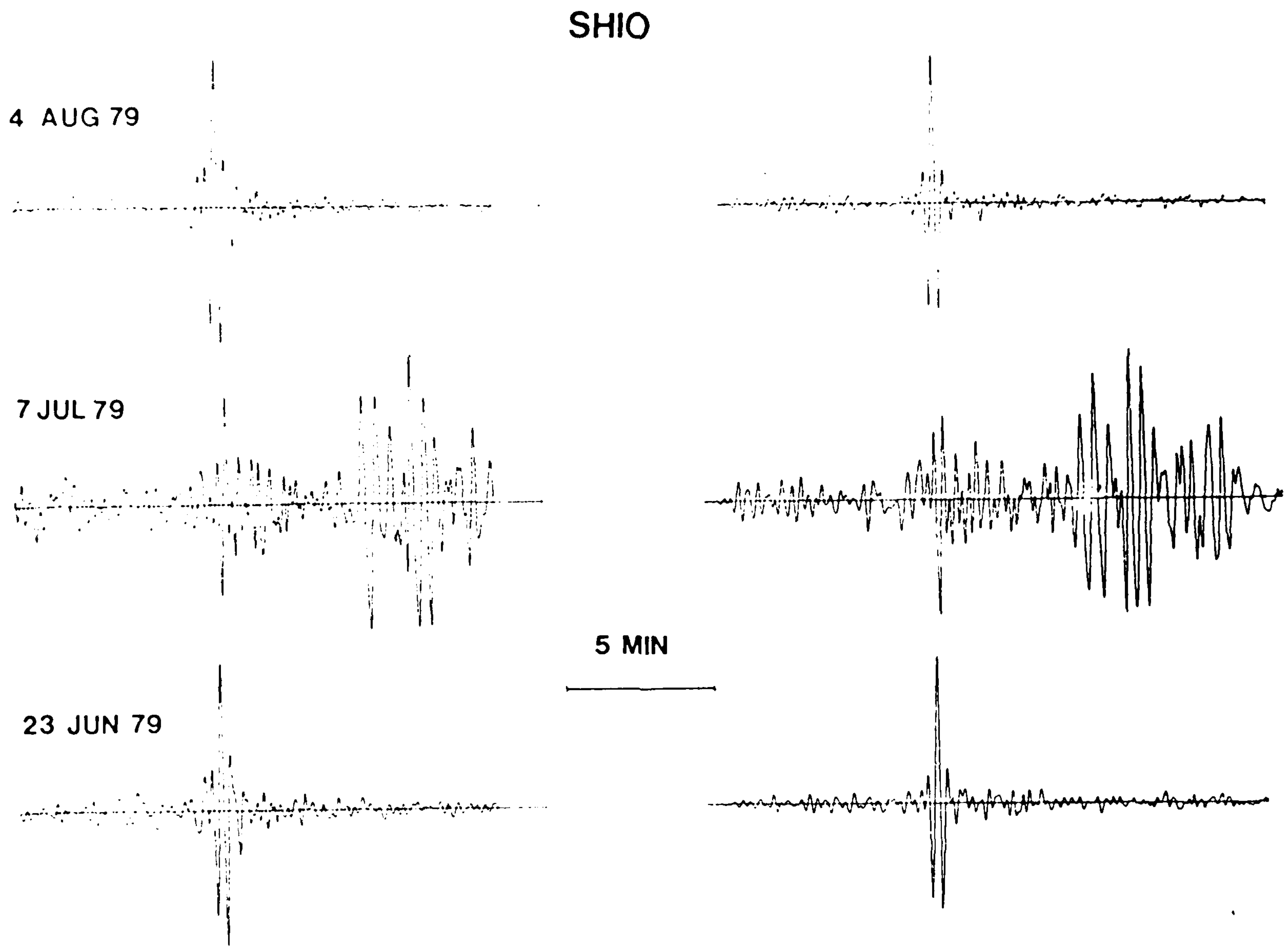
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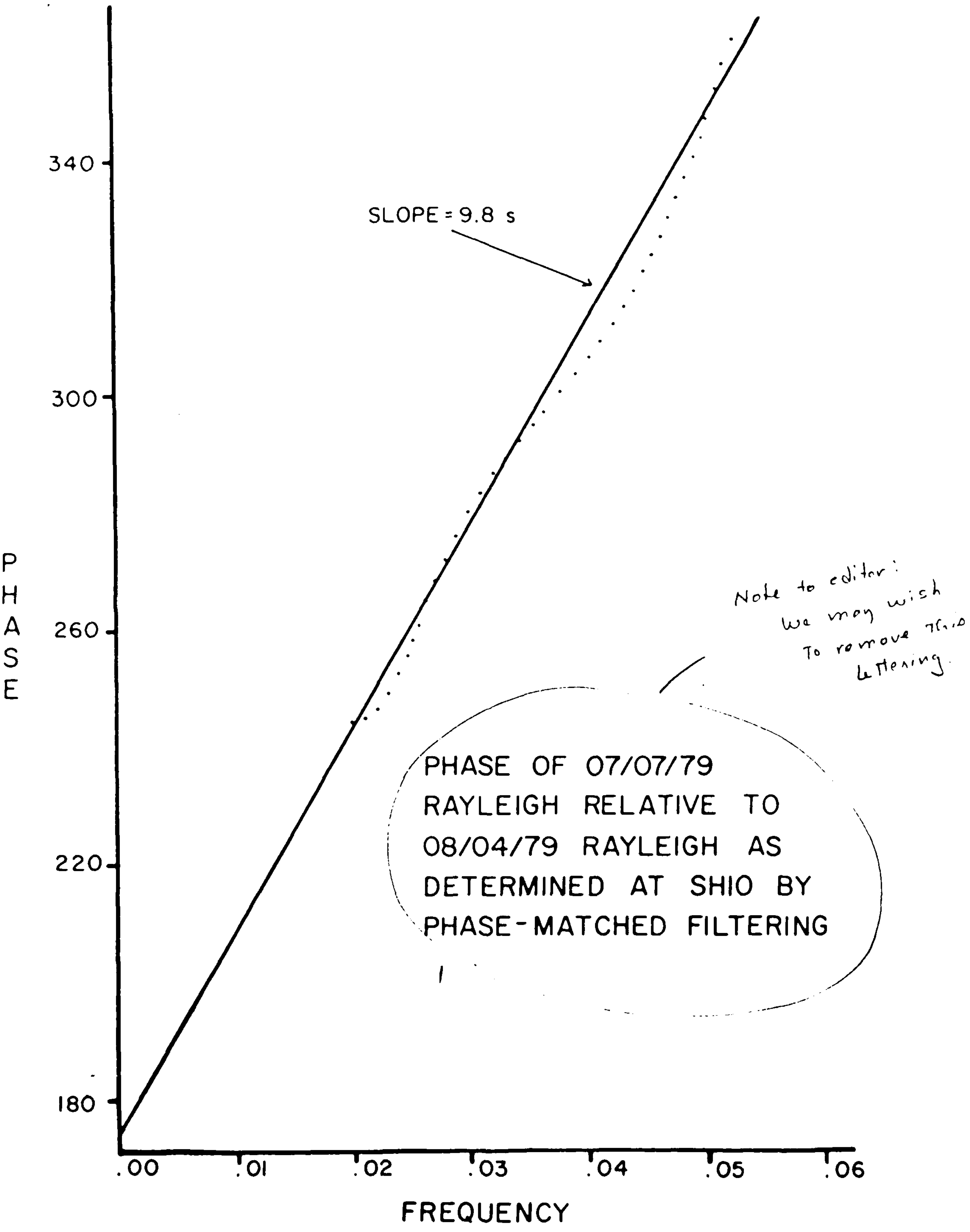
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Figure 14

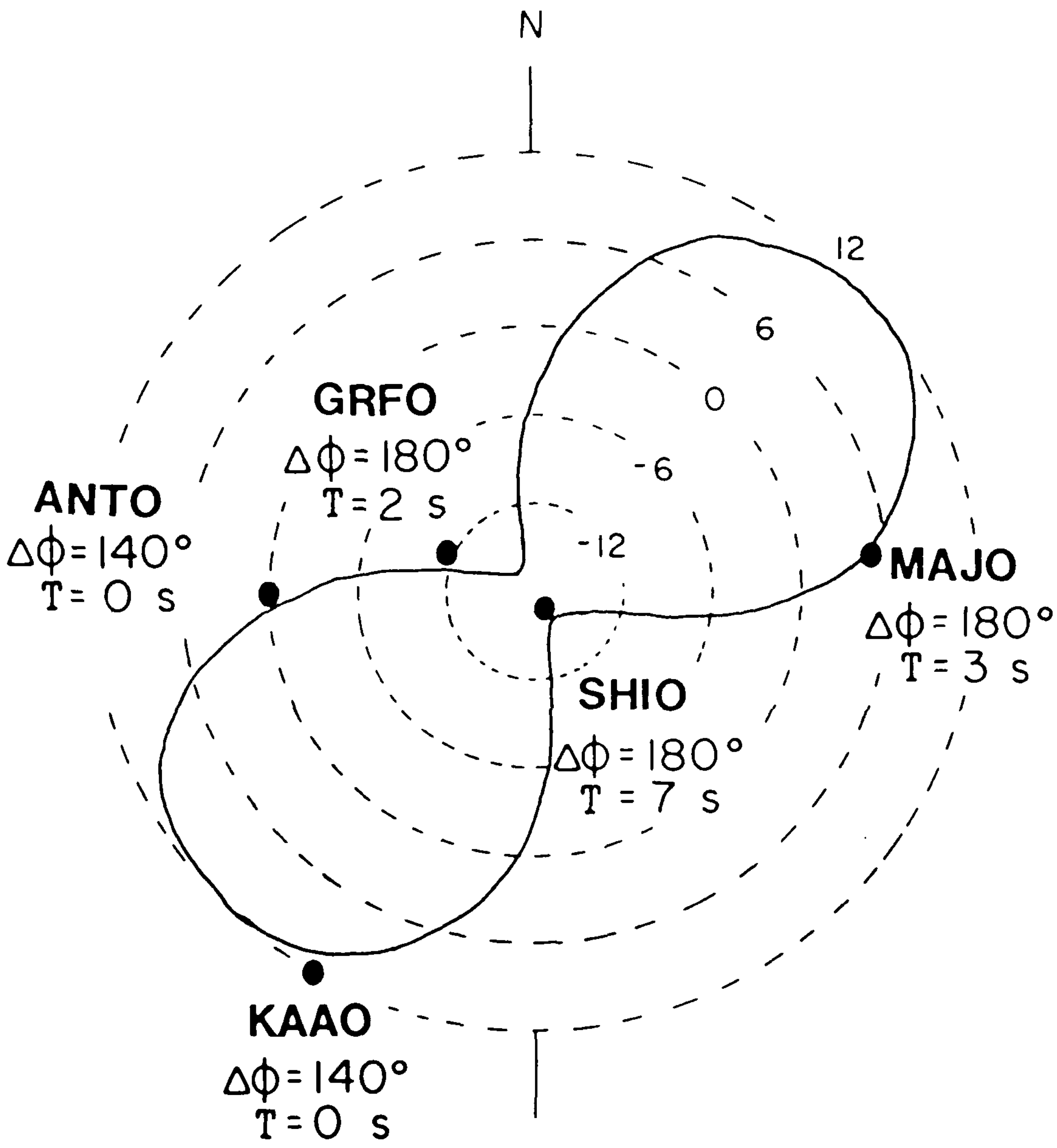

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Figure 15

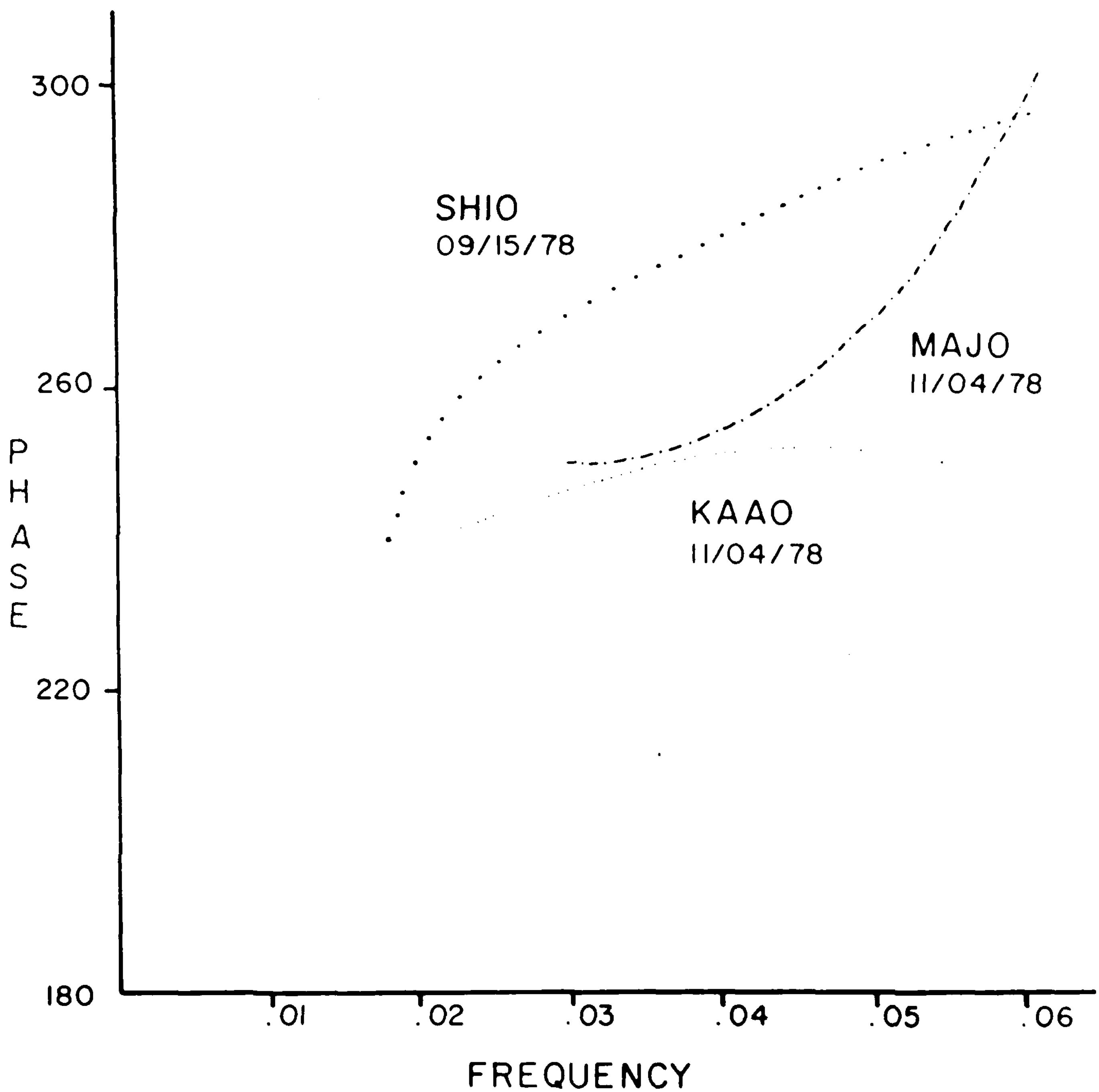
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Figure 16

JPL
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

TELECOMMUNICATIONS MESSAGE

7-1

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OR FTS 792-3

ATTN:		PHONE OF ADDRESSEE	
JAMES E. BRUSETH		214, 692-2033	
ORGANIZATION: SOUTHERN METHODIST UNIVERSITY			
STREET: —			
CITY: DALLAS	STATE & COUNTRY: TX, USA	ZIP CODE: 75275	
TRANSMIT NUMBER (TWX, TELEX, FAX): FAX (214) 692-4099	DATE & TIME REQ. AT DEST.: 6/2/87 12:00 P.M PDT (2:00 P.M CDT)		
FROM: JOHN M. WALSH	PHONE EXT.: 42628	MAIL STOP: 202-217	
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MESSAGE TO SMU FAX ROOM!

PLEASE PHONE MR. BRUSETH
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Thank you,
J. WALSH.

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1. CLASSIFIED MATERIAL CANNOT BE TRANSMITTED VIA THE TELECOMMUNICATIONS NETWORKS.
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California Institute of Technology
4800 Oak Grove Drive
Pasadena California 91109
(818) 354-4321

7-2 JPL

2 June 1987

SOUTHERN METHODIST UNIVERSITY
Dallas, Texas 75275

Attention: James E. Bruseth
Director Office of Research Administration

Subject: Fact-finding questions pertaining to SMU proposal for the Extension to JPL Contract No. 957072

Reference: Telecon between J. Bruseth (SMU) and J. Walsh (JPL) on 2 June 1987.

This memo is to provide you with formal documentation of the fact-finding questions and requests which I relayed to you during the referenced telephone conversation. It is my understanding that you will provide me with responses to these questions and requests via FAX as soon as they are available.

LABOR HOURS/LABOR RATES

1.) The SMU proposal claims that the old Magellan budget provided for a full-time Graduate Research Assistant for FY 87/88/89. JPL records indicate that the old budget provides for a Graduate Research Assistant for FY 87/88/89, but at only half-time (Contract Mod no. 1).

The hourly rate negotiated for this half-time Graduate Research Assistant, according to JPL records of Contract Mod no. 1, ranged from $9.00 in 1987 to $9.82 in 1989. The hourly rate proposed for the full-time Graduate Research Assistant in the Mod no. 2 proposal by SMU ranges from $4.62 in 1987 to $5.77 in 1991.

Would SMU please investigate and explain?

COMPUTER EQUIPMENT/MAINTENANCE

2.) Please provide back-up documentation for the following computer equipment costs included in your bid:

Sun-3/280S Data Center Server
Color Monitor Board/Keyboard/Mouse
575 MBYTE Disk
Data Center Cabinet

Jet Propulsion Laboratory
California Institute of Technology

7-3

3.) During which month in FY 1988 will the computer equipment be delivered? How many months of free maintenance will come with the purchase price of the computer?

4.) Mod no.1 negotiated Computer Maintenance costs at a rate of $450/mo. Please provide backup for the increase to $507/mo on this proposal.

TRAVEL

5.) Please provide back-up for the $3000 bid for FY87 travel.

TELEPHONE

6.) Please provide back-up for the $700 bid for FY87 telephone costs.

ACTUAL COSTS THRU FY 1986

7.) Please provide the actual costs incurred against this contract thru 09/30/86.

Thank you for your cooperation.

Sincerely,

John M. Walsh
Cost Analyst

cc: S. Dallas 264-316
N. Nickle 264-316
C. Sears 264-370

END
8-87
DTIC